GAIN IMPROVEMENT OF ER-DOPED AMPLIFIERS FOR THE FEEDBACK FILTERS

A Dissertation

by

XIAOMIN SONG

Submitted to the Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2011

Major Subject: Electrical Engineering
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Approved by:

Chair of Committee, Christi K. Madsen
Committee Members, Ohannes Eknoyan
Kai Chang
Jairo Sinova
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ABSTRACT

Gain Improvement of Er-doped Amplifiers for the Feedback Filters.

(December 2011)

Xiaomin Song, B.S., Tsinghua University;
M.S., Tsinghua University

Chair of Advisory Committee: Dr. Christi K. Madsen

The combination of the arsenic trisulfide (As$_2$S$_3$) waveguide and titanium diffused lithium niobate (Ti:LiNbO$_3$) waveguide provide us compact and versatile means for transmitting and processing optical signals, which benefits from the high index contrast between these two materials and the electro-optical properties of Ti: LiNbO$_3$. Furthermore, waveguide gain is introduced through selective surface erbium (Er) doping which yields high quality loss-compensated or even amplifying waveguides without disturbing the excellent electrooptical, acoustooptical and nonlinear properties of the waveguide substrate LiNbO$_3$. The integration of these waveguides allows the development of a whole class of new waveguide devices of higher functionality and complexity.

As one kind of the hybrid waveguide devices, a new configuration consisting of an As$_2$S$_3$ channel waveguide on top of an Er doped titanium diffused x-cut lithium niobate waveguide has been investigated by simultaneous analytical expressions, numerical simulations, and experimentation. Both simulation and experimental results have shown that this structure can enhance the optical gain, as predicted by the analytical expressions. An
As$_2$S$_3$ channel waveguide has been fabricated on top of a conventional Er:Ti:LiNbO$_3$ waveguide, where the higher refractive index As$_2$S$_3$ waveguide is used to pull the optical mode towards the substrate surface where the higher Er concentration yields an improved propagation gain. The relationship between the gain and As$_2$S$_3$ layer thickness has been evaluated, and the optimal As$_2$S$_3$ thickness was found by simulation and experimentation. Side integration was applied to reduce the extra propagation loss caused by the titanium diffusion bump. The propagation gain (dB/cm) has been improved from 1.1 to 2 dB/cm.

Another hybrid device which combines the As$_2$S$_3$ and LiNbO$_3$ is to make an As$_2$S$_3$ racetrack ring resonator on top of an x-cut y-propagation Er:Ti:LiNbO$_3$ waveguide, which is the potential structure for integrated lossless all-path filter. The ring was side-coupled with the Ti:LiNbO$_3$ waveguide, and the optical gain was achieved when the 5mm long coupling region where it has been diffused with Er in advance pumped by a 144mW pump laser. The free spectral range (FSR) of the measured ring response for TM mode is 0.0587nm (7.33GHz) at 1550nm. The roundtrip loss are 4.4dB (2.60dB/cm) when pump on and 5.8dB (3.44dB/cm) when pump off. The optical gain in the Er diffused area is 0.72dB/cm.
DEDICATION

To my family
I would like to thank my advisor and committee chair, Dr. Christi K. Madsen, for her expert guidance, encouragement and constant support during my dissertation work. I am also grateful to other committee members, Dr. Ohannes Eknoyan, Kai Chang, Jairo Sinova, for their time and effort in guiding and supporting me throughout the course of this research.

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Finally, I would like to thank my beloved wife Emma, my parents and my sister for their unconditional love and support.
TABLE OF CONTENTS

ABSTRACT .................................................................................................................. iii

DEDICATION ............................................................................................................. v

ACKNOWLEDGEMENTS ........................................................................................... vi

TABLE OF CONTENTS ............................................................................................. vii

LIST OF FIGURES ...................................................................................................... ix

LIST OF TABLES ....................................................................................................... xv

CHAPTER

I INTRODUCTION............................................................................................ 1

1.1. Background and motivation ................................................................. 1

1.1.1. Background .................................................................................... 1

1.1.2. Materials ......................................................................................... 2

1.2. Previous work............................................................................................ 5

1.2.1. As$_2$S$_3$ assisted Er:Ti: LiNbO$_3$ ......................................................... 6

1.2.2. As$_2$S$_3$ ring and cavity on Er:Ti:LiNbO$_3$ ......................................... 7

1.3. Organization of the dissertation ................................................................. 8

II THEORETICAL REVIEW ............................................................................ 10

2.1. Electromagnetic theory and waveguide mode solving ......................... 10

2.1.1. Electromagnetic theory .................................................................... 10

2.1.2. Numerical solvers ............................................................................ 14

2.2. Optical waveguides modeling ................................................................. 16

2.2.1. Modeling of the Ti: LiNbO$_3$ ............................................................... 16

2.2.2. Modeling of the Er diffusion in LiNbO$_3$ ........................................... 21

2.2.3. Modeling of the Er gain .................................................................... 23

2.3. Ring resonator theory .............................................................................. 24

2.4. Electro-optical effect ............................................................................... 28

2.5. Multilayer and Bragg grating reflectors .................................................. 31

2.5.1. Multilayer reflector .......................................................................... 31

2.5.2. Bragg grating reflector ...................................................................... 36
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>SIMULATION</td>
</tr>
<tr>
<td>3.1. Ti:LiNbO₃ waveguides</td>
<td>38</td>
</tr>
<tr>
<td>3.1.1. Titanium diffusion parameters</td>
<td>39</td>
</tr>
<tr>
<td>3.1.2. Basic Ti:LiNbO₃ waveguide simulations</td>
<td>40</td>
</tr>
<tr>
<td>3.1.3. Coupling loss between Ti:LiNbO₃ modes and fiber modes</td>
<td>43</td>
</tr>
<tr>
<td>3.2. Hybrid waveguides</td>
<td>47</td>
</tr>
<tr>
<td>3.2.1. Er doped Ti:LiNbO₃ waveguides</td>
<td>47</td>
</tr>
<tr>
<td>3.2.2. As₂S₃ waveguides on top of the Ti:LiNbO₃ waveguides</td>
<td>65</td>
</tr>
<tr>
<td>3.3. Electro-optical devices</td>
<td>74</td>
</tr>
<tr>
<td>3.3.1. As₂S₃ waveguide assisted EO phase shifter</td>
<td>74</td>
</tr>
<tr>
<td>3.3.2. Nano-slot EO phase shifter</td>
<td>80</td>
</tr>
<tr>
<td>3.4. Multilayer and Bragg reflectors</td>
<td>84</td>
</tr>
<tr>
<td>3.4.1. Multilayer reflectors</td>
<td>84</td>
</tr>
<tr>
<td>3.4.2. Bragg grating reflectors</td>
<td>87</td>
</tr>
<tr>
<td>IV</td>
<td>FABRICATION AND PROCESS DEVELOPMENT</td>
</tr>
<tr>
<td>4.1. As₂S₃ waveguide assisted Er: Ti: LiNbO₃</td>
<td>94</td>
</tr>
<tr>
<td>4.2. As₂S₃ ring on Er: Ti: LiNbO₃</td>
<td>95</td>
</tr>
<tr>
<td>4.2.1. Image reversal</td>
<td>95</td>
</tr>
<tr>
<td>4.2.2. Lift-off</td>
<td>96</td>
</tr>
<tr>
<td>4.3. Er doped Ti: LiNbO₃ cavity</td>
<td>97</td>
</tr>
<tr>
<td>4.3.1. Multilayer deposition</td>
<td>97</td>
</tr>
<tr>
<td>4.3.2. E-beam lithography for Bragg grating</td>
<td>99</td>
</tr>
<tr>
<td>V</td>
<td>MEASUREMENTS AND RESULTS</td>
</tr>
<tr>
<td>5.1. As₂S₃ waveguide assisted Er: Ti: LiNbO₃</td>
<td>107</td>
</tr>
<tr>
<td>5.2. As₂S₃ ring on Er: Ti: LiNbO₃</td>
<td>109</td>
</tr>
<tr>
<td>5.3. Er doped Ti: LiNbO₃ cavity</td>
<td>117</td>
</tr>
<tr>
<td>5.3.1. Multilayer measurement</td>
<td>117</td>
</tr>
<tr>
<td>5.3.2. E-beam lithography results</td>
<td>125</td>
</tr>
<tr>
<td>VI</td>
<td>CONCLUSION</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>133</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>138</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>140</td>
</tr>
<tr>
<td>VITA</td>
<td>142</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>As$_2$S$_3$</td>
</tr>
<tr>
<td>2</td>
<td>Lithium niobate crystal structure</td>
</tr>
<tr>
<td>3</td>
<td>Erbium Doped Fiber Amplifier (EDFA)</td>
</tr>
<tr>
<td>4</td>
<td>Reflection and refraction</td>
</tr>
<tr>
<td>5</td>
<td>Total internal reflection</td>
</tr>
<tr>
<td>6</td>
<td>As$_2$S$_3$ ring side coupled to Ti:LiNbO$_3$ waveguide: (a) Schematic structure; (b) SEM image of the fabricated ring device: side-coupling region</td>
</tr>
<tr>
<td>7</td>
<td>Transmission and group delay response of the ring structure</td>
</tr>
<tr>
<td>8</td>
<td>Normalized amplitude response, $\rho = 0.98$</td>
</tr>
<tr>
<td>9</td>
<td>Normalized amplitude response, $\gamma = 0.5dB$</td>
</tr>
<tr>
<td>10</td>
<td>Index ellipsoid of lithium niobate.</td>
</tr>
<tr>
<td>11</td>
<td>Extraordinary (left) and ordinary (right) refractive index distributions calculated using optiBPM</td>
</tr>
<tr>
<td>12</td>
<td>Calculated power density distributions for the TE and TM fundamental optical modes</td>
</tr>
<tr>
<td>13</td>
<td>Calculated and measured horizontal mode profiles for the TE and TM fundamental optical modes in 2D</td>
</tr>
<tr>
<td>14</td>
<td>Calculated and measured vertical mode profiles for the TE and TM fundamental optical modes in 2D</td>
</tr>
<tr>
<td>15</td>
<td>Mode size comparison between TE, TM and fiber</td>
</tr>
<tr>
<td>16</td>
<td>Ti:LiNbO$_3$ waveguide mode solving</td>
</tr>
<tr>
<td>17</td>
<td>Er density distribution</td>
</tr>
<tr>
<td>18</td>
<td>The calculation of overlap between mode and Er distribution</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>38</td>
<td>Propagation gain versus pump power for Er:Ti:LiNbO₃ waveguide without As₂S₃ for TM mode.</td>
</tr>
<tr>
<td>39</td>
<td>Effective gain influenced by pump effects for TM mode.</td>
</tr>
<tr>
<td>40</td>
<td>Propagation gain versus As₂S₃ thickness: Comparing measured and simulated results for TM mode (peak at 280 nm).</td>
</tr>
<tr>
<td>41</td>
<td>Propagation gain versus As₂S₃ thickness: Simulated results for TE mode (peak at 200 nm).</td>
</tr>
<tr>
<td>42</td>
<td>Coupling overlap (coupling loss) for TM and TE modes.</td>
</tr>
<tr>
<td>43</td>
<td>MZI pattern with 1um gap between Ti (or As₂S₃) and electrodes (The gap is the distance between Ti (or As₂S₃) and electrodes).</td>
</tr>
<tr>
<td>44</td>
<td>EO effect simulation for TM modes.</td>
</tr>
<tr>
<td>45</td>
<td>EO effect simulation for TE modes.</td>
</tr>
<tr>
<td>46</td>
<td>Potential of the asymmetrical electrodes.</td>
</tr>
<tr>
<td>47</td>
<td>Potential of the symmetrical electrodes.</td>
</tr>
<tr>
<td>48</td>
<td>EO_nano_slot FIMMwave setup.</td>
</tr>
<tr>
<td>49</td>
<td>2D Ex field of nano slot from complex solver (TE mode).</td>
</tr>
<tr>
<td>50</td>
<td>3D Ex field of nano slot from complex solver (TE mode).</td>
</tr>
<tr>
<td>51</td>
<td>Intensity and phase reflectance at center wavelength (1531nm).</td>
</tr>
<tr>
<td>52</td>
<td>Reflectance when number of the high &amp; low pairs N=1,2,3.</td>
</tr>
<tr>
<td>53</td>
<td>Reflectance when number of the high &amp; low pairs N=7.</td>
</tr>
<tr>
<td>54</td>
<td>Schematic illustration of the waveguide with Bragg gratings.</td>
</tr>
<tr>
<td>55</td>
<td>Broadband transmittance spectrum for TE input polarization.</td>
</tr>
<tr>
<td>56</td>
<td>Transmittance and reflectance simulation for Si overlay Bragg grating (TE mode, 10e6 periods).</td>
</tr>
<tr>
<td>57</td>
<td>Taper teeth structure FimmProp simulation setup.</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>----------</td>
<td>------</td>
</tr>
<tr>
<td>58</td>
<td>91</td>
</tr>
<tr>
<td>58 Broadband transmittance and reflection simulation for As$_2$S$_3$ WG Bragg grating (TM mode, 5000 periods, length=1.72 mm).</td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>92</td>
</tr>
<tr>
<td>59 Single unit period of the four-section design of Bragg grating.</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>93</td>
</tr>
<tr>
<td>60 Whole length of the four-section design of Bragg grating.</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>93</td>
</tr>
<tr>
<td>61 Generated GDS file of the Bragg grating.</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>95</td>
</tr>
<tr>
<td>62 The Er concentration profile measured by Secondary Ion Mass Spectrometry (SIMS).</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>95</td>
</tr>
<tr>
<td>63 Top-view photomicrograph of Ti:LiNbO$_3$ and As$_2$S$_3$ waveguides.</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>96</td>
</tr>
<tr>
<td>64 Photograph of an ideal development.</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>97</td>
</tr>
<tr>
<td>65 Samples were set face down during the lift-off.</td>
<td></td>
</tr>
<tr>
<td>66</td>
<td>98</td>
</tr>
<tr>
<td>66 Multilayer films.</td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>99</td>
</tr>
<tr>
<td>67 AJA facet deposition mount.</td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>100</td>
</tr>
<tr>
<td>68 E-gun chamber in room 1 (with load lock).</td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>101</td>
</tr>
<tr>
<td>69 Main console in room 2.</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>101</td>
</tr>
<tr>
<td>70 Cassette holder lock.</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>102</td>
</tr>
<tr>
<td>71 Auto loader (wafer transfer) control.</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>104</td>
</tr>
<tr>
<td>72 RC620, NEB 3’30” in the etching process.</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>104</td>
</tr>
<tr>
<td>73 RC607, ZEP, after 4’30” RIE etching.</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>106</td>
</tr>
<tr>
<td>74 Design diagram of As$_2$S$_3$ grating by E-beam lithography.</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>106</td>
</tr>
<tr>
<td>75 Selective deposited sample.</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>107</td>
</tr>
<tr>
<td>76 Schematic of the propagation gain measurement.</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>109</td>
</tr>
<tr>
<td>77 Propagation gain spectrum with and without As$_2$S$_3$ on LiNbO$_3$ for TM mode (As$_2$S$_3$ thickness=280 nm).</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>110</td>
</tr>
<tr>
<td>78 Erbium area, As$_2$S$_3$ ring and titanium WG on the mask design.</td>
<td></td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>79 Picutre of Er and Ti diffused areas.</td>
<td>110</td>
</tr>
<tr>
<td>80 Gain measurement without As$_2$S$_3$ ring.</td>
<td>111</td>
</tr>
<tr>
<td>81 Gain measurement with As$_2$S$_3$ ring.</td>
<td>112</td>
</tr>
<tr>
<td>82 Ring response (RC436, zoom in, pump on).</td>
<td>112</td>
</tr>
<tr>
<td>83 Ring response when pump is on (RC534, air cladding).</td>
<td>114</td>
</tr>
<tr>
<td>84 Ring response when pump is off (RC534, air cladding).</td>
<td>114</td>
</tr>
<tr>
<td>85 Fitted magnitude and group delay (at wavelength=1547.9 nm, pump on)</td>
<td>115</td>
</tr>
<tr>
<td>86 Er luminescence with backward pump on: Darker in the center</td>
<td>116</td>
</tr>
<tr>
<td>87 Ring and GT structure.</td>
<td>118</td>
</tr>
<tr>
<td>88 Ring and GT structure comparison</td>
<td>118</td>
</tr>
<tr>
<td>89 Reflection measurement steps.</td>
<td>119</td>
</tr>
<tr>
<td>90 TE and TM SUM out unfiltered insertion loss.</td>
<td>120</td>
</tr>
<tr>
<td>91 TE to TE unfiltered insertion loss.</td>
<td>120</td>
</tr>
<tr>
<td>92 TM to TM unfiltered insertion loss.</td>
<td>120</td>
</tr>
<tr>
<td>93 Time Domain filtering.</td>
<td>121</td>
</tr>
<tr>
<td>94 TE and TM SUM out filtered insertion loss</td>
<td>121</td>
</tr>
<tr>
<td>95 TE to TE filtered insertion loss.</td>
<td>122</td>
</tr>
<tr>
<td>96 TM to TM filtered insertion loss.</td>
<td>122</td>
</tr>
<tr>
<td>97 Photo of RC283 at multilayer cavity measurement</td>
<td>123</td>
</tr>
<tr>
<td>98 RC283 multilayer result when pump on.</td>
<td>124</td>
</tr>
<tr>
<td>99 RC283 multilayer result when pump off.</td>
<td>124</td>
</tr>
<tr>
<td>100 Fitted Data at wavelength=1531 nm (f=1.9581e14Hz, TM, pump on)</td>
<td>125</td>
</tr>
<tr>
<td>101 SEM photo: ZEP, dose 99 μC/cm$^2$, lower amplification.</td>
<td>126</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>102 SEM photo: ZEP, dose 81 $\mu$C/cm$^2$</td>
<td>127</td>
</tr>
<tr>
<td>103 SEM photo: ZEP, dose 99 $\mu$C/cm$^2$</td>
<td>127</td>
</tr>
<tr>
<td>104 SEM photo: ZEP, dose 117 $\mu$C/cm$^2$</td>
<td>128</td>
</tr>
<tr>
<td>105 SEM photo: NEB, dose 14 $\mu$C/cm$^2$, lower amplification</td>
<td>129</td>
</tr>
<tr>
<td>106 SEM photo: NEB, dose 10 $\mu$C/cm$^2$</td>
<td>129</td>
</tr>
<tr>
<td>107 SEM photo: NEB, dose 12 $\mu$C/cm$^2$</td>
<td>130</td>
</tr>
<tr>
<td>108 SEM photo: NEB, dose 14 $\mu$C/cm$^2$</td>
<td>130</td>
</tr>
</tbody>
</table>
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Titanium depletion time</td>
<td>19</td>
</tr>
<tr>
<td>II</td>
<td>Er depletion time: (1) is from $C_0^1$, (2) is from $C_0^2$</td>
<td>22</td>
</tr>
<tr>
<td>III</td>
<td>Experimental and simulated mode width data comparison</td>
<td>39</td>
</tr>
<tr>
<td>IV</td>
<td>Overlap between waveguide and fiber mode for TE mode</td>
<td>45</td>
</tr>
<tr>
<td>V</td>
<td>Overlap between waveguide and fiber mode for TM mode</td>
<td>46</td>
</tr>
<tr>
<td>VI</td>
<td>Overlap versus Ti thickness and diffusion time for TE mode</td>
<td>51</td>
</tr>
<tr>
<td>VII</td>
<td>Overlap versus Ti thickness and diffusion time for TM mode</td>
<td>52</td>
</tr>
<tr>
<td>VIII</td>
<td>Pump laser parameters</td>
<td>53</td>
</tr>
<tr>
<td>IX</td>
<td>CW laser parameters</td>
<td>53</td>
</tr>
<tr>
<td>X</td>
<td>Er ion density setup</td>
<td>54</td>
</tr>
<tr>
<td>XI</td>
<td>Gain (dB) versus Er$<em>{D</em>{eff}}$</td>
<td>54</td>
</tr>
<tr>
<td>XII</td>
<td>Gain (dB) versus Er strip width</td>
<td>57</td>
</tr>
<tr>
<td>XIII</td>
<td>Up-conversion parameters</td>
<td>59</td>
</tr>
<tr>
<td>XIV</td>
<td>Pump parameters setup</td>
<td>59</td>
</tr>
<tr>
<td>XV</td>
<td>Setting for sweeping Er metastable lifetime</td>
<td>61</td>
</tr>
<tr>
<td>XVI</td>
<td>Setting for sweeping Er ion density..</td>
<td>62</td>
</tr>
<tr>
<td>XVII</td>
<td>Propagation gain versus Er thickness..</td>
<td>63</td>
</tr>
<tr>
<td>XVIII</td>
<td>EO effects for TM modes: Varying As$_2$S$_3$ width and electrodes gap</td>
<td>77</td>
</tr>
<tr>
<td>XIX</td>
<td>EO effects for TE modes: Varying As$_2$S$_3$ width and electrodes gap</td>
<td>77</td>
</tr>
<tr>
<td>XX</td>
<td>EO results when window size= 4 $\mu$m*7 $\mu$m, slot filled with air</td>
<td>83</td>
</tr>
<tr>
<td>XXI</td>
<td>EO results when window size= 2 $\mu$m*3 $\mu$m, slot filled with air</td>
<td>84</td>
</tr>
<tr>
<td>TABLE</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>XXII</td>
<td>EO results when window size= 2 μm*3 μm, slot filled with LiNbO$_3$........ 84</td>
<td></td>
</tr>
<tr>
<td>XXIII</td>
<td>Parameters of Bragg grating (TE polarization, *thickness: etched)............. 87</td>
<td></td>
</tr>
<tr>
<td>XXIV</td>
<td>Image reversal recipe. ................................................................................. 96</td>
<td></td>
</tr>
<tr>
<td>XXV</td>
<td>Multilayer index and thicknesses. .............................................................. 98</td>
<td></td>
</tr>
<tr>
<td>XXVI</td>
<td>Er ring parameters. ................................................................................... 110</td>
<td></td>
</tr>
<tr>
<td>XXVII</td>
<td>RC436 fitted round trip loss and coupling ratio. ........................................... 113</td>
<td></td>
</tr>
<tr>
<td>XXVIII</td>
<td>RC543 ring parameters. .............................................................................. 113</td>
<td></td>
</tr>
<tr>
<td>XXIX</td>
<td>RC543 fitted results. .................................................................................. 115</td>
<td></td>
</tr>
<tr>
<td>XXX</td>
<td>RC283 cavity fitted results. ......................................................................... 125</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

1.1. Background and motivation

1.1.1. Background

The field of integrated optics has a significant development during the last two decades along with the explosive growth of the fiber telecommunication systems. These developments require a correspondingly large number of optical components no matter passive devices such as splitters, couplers, multiplexers, switches, filters, modulators etc, or active components like optical sources, detectors, and optical amplifiers. Most of these components have been realized in integrated-optic form.

The integrated active feedback filters possess intrinsic merits which are pursued by the researchers in the area of integrated optics: smaller size, lower cost, more powerful functionality and design flexibility. Resonators based reconfigurable optical devices with feedback paths including rings and Gires-Tournois interferometers (cavities) are attractive since they can work as switches, modulators, multiplexers and filters as well.

Among these applications based on resonators, the lossless all-pass filter (APF) can be one of the hotspots in this area. Such filters can generate large group delay and dispersion without any amplitude distortion, and have been used in tunable dispersion

This dissertation follows the style of Journal of Lightwave Technology.
compensation [1-4], dispersion slope compensation [5], optical delay lines [6] and as building blocks in tunable band-pass filters where multiple stages of all-pass filters are cascaded or latticed.

To achieve the “loss-less” capability which contradicts to the inherent characteristic of loss for every media, the optical gain is required to be introduced through the feedback path.

This work concentrates on the gain improvement of the amplifiers for compensating the loss throughout the feedback path in the all-pass filters which serve as the basic building block for integrated optical signal processing. The increase of the gain can be realized by several improvements on waveguide design, fabrication technique and equipment enhancement. The detailed inspected parameters include: material chosen, waveguide dimensions design (thickness, width and length), index profile, mode overlap calculation, gain modeling, coupling tip shape, photolithography recipe, etc. They will be discussed all through this dissertation.

1.1.2. Materials

This section will introduce three major materials used in the research. The integrated optical devices discussed above are fabricated by these materials.

As$_2$S$_3$ (Fig. 1) is one kind of amorphous chalcogenide glass which is a chemical compound consisting of at least one chalcogen ion and at least one more electropositive element. Although all group 16 elements of the periodic table are defined as chalcogens, the term is more commonly reserved for sulfides, selenides, and tellurides, rather than
oxides. $\text{As}_2\text{S}_3$ has very good optical properties. It is transparent between 620 nm and 11 µm with large refractive index around 2.4. And it also has large nonlinearity [7].

Fig. 1. $\text{As}_2\text{S}_3$ [8].

Lithium niobate (LiNbO$_3$ or LN) is a birefringent crystal (Fig. 2) that has long been utilized as the substrate material for its strong tuning capability. It is a compound of niobium, lithium, and oxygen and its single crystals are an important material for optical waveguides, mobile phones, optical modulators and various other linear and non-linear optical applications [9].

Fig. 2. Lithium niobate crystal structure [9].
LiNbO$_3$ has wide transmission range: 420 nm~5.2 $\mu$m. It has excellent electric-optical and non-linear properties. The LiNbO$_3$ wafers that have been used in the research work are x-cut, y-propagation, two inches in diameter and 1or 0.5mm thick.

Titanium diffused waveguides in lithium niobate substrate (Ti: LiNbO$_3$), as being well developed for thirty years, has excellent electro-optical properties, low propagation loss and low coupling loss to optical fiber [10, 11] which has been used as the foundation of our devices.

Erbium is a rare earth element in the lanthanide series, with the symbol Er and atomic number 68. It is a silvery-white solid metal when artificially isolated. Natural erbium is always found in chemical combination with other elements on Earth. Erbium's principal uses involve its pink-colored Er$^{3+}$ ions, which have optical fluorescent properties particularly useful in certain laser applications [12]. Erbium-doped glasses or crystals can be used as optical amplification media, where Er$^{3+}$ ions are optically pumped at around 980 nm or 1480 nm and then radiate light at 1530 nm in stimulated emission. This process results in an unusually mechanically simple laser optical amplifier for fiberoptically transmitted signals. The 1550 nm wavelength is especially important for optical communications because standard single mode optical fibers have minimal loss at this particular wavelength. The most common example is the Erbium Doped Fiber Amplifier (EDFA) (Fig. 3 from internet), where the core of a silica fiber is doped with trivalent Erbium ions and can be efficiently pumped with a laser at a wavelength of 980 nm or 1,480 nm, and exhibits gain in the 1,550 nm regions.
Erbium (Er) diffused titanium diffused lithium niobate (Ti:LiNbO₃) waveguides have also been extensively investigated [13]. Positive gain has been achieved to overcome the propagation loss and even high enough to make lasers [14-16].

1.2. Previous work

The combination of the As₂S₃ waveguide and Ti:LiNbO₃ waveguide provide us compact and versatile approaches for transmitting and processing optical signals, which benefits from the high index contrast between these two materials and the electro-optical properties of Ti: LiNbO₃. Furthermore, waveguide gain can be introduced through selective surface erbium doping which yields high quality loss-compensated or even amplifying waveguides without disturbing the excellent electrooptical, acoustooptical and nonlinear properties of the waveguide substrate LiNbO₃. The integration of these waveguides allows the development of a whole class of new waveguide devices of higher functionality and complexity.
1.2.1. **As$_2$S$_3$ assisted Er: Ti: LiNbO$_3$**

Erbium doped Ti:LiNbO$_3$ waveguides have been widely explored [13]. The overlap between the optical fields and Er ions has been related to the optical gain [15] which has been achieved to overcome the propagation loss and even high enough to make lasers [14-16]. It is well-known that the propagation gain is proportional to the overlap between the optical mode and Er profile.

For the surface in-diffused Er profile, achieving a high overlap requires pulling the optical mode closer to the surface, where the Er concentration is higher. To achieve the mode pulling, a blanket-clad TiO$_2$ configuration has been reported with estimates on the gain improvement [17]. Arsenic trisulfide is a better choice for mode pulling owing to its high refractive index. Other benefits include a high nonlinear coefficient, low propagation loss, and low processing temperature. In this paper, we focus on the gain improvement by using a patterned As$_2$S$_3$ waveguide on top of a straight Er:Ti:LiNbO$_3$ to elevate the mode. Utilizing a straight channel As$_2$S$_3$ waveguide instead of a blanket film not only improves the gain, but also reduces the propagation loss by side coupling. We have found that surface roughness from the Ti diffused bump will introduce excess losses if the As$_2$S$_3$ waveguide sits on top of the diffused waveguide. Hence, the As$_2$S$_3$ layer is patterned next to the titanium bump to utilize side coupling and avoid the losses associated with the non-planar bump surface. Furthermore, the patterned As$_2$S$_3$ waveguide enables vertically integrated structures, which combines the As$_2$S$_3$ waveguide above the substrate surface and the Er:Ti:LiNbO$_3$ waveguide below the surface, such as Mach Zehnder Interferometers (MZI) and rings [18, 19].
We also investigated the range of As$_2$S$_3$ thicknesses that enhance the optical gain, and found the optimum As$_2$S$_3$ waveguide parameters through simulations and confirmed in experimentation.

1.2.2. As$_2$S$_3$ ring and cavity on Er: Ti: LiNbO$_3$

The integrated resonator based reconfigurable optical devices with feedback paths are attracting interests recently. They have various applications such as modulators [20], optical filters and multiplexers [21].

All-pass filters (APF’s) are resonant devices that allow any desired phase correction or equalization without introducing any amplitude distortion [2], which means it can produce strong on-resonance phase variation while maintaining unity reflectance or transmission. The structural losslessness property induces its robust performance [22].

As the computationally efficient signal processing building blocks which are quite useful in many signal processing applications [22], such filters can generate large group delay and dispersion, and have been used in tunable dispersion compensation [1-4], dispersion slope compensation [5], optical delay lines [6] and as building blocks in tunable band pass filters where multiple stages of all-pass filters are cascaded or latticed. Furthermore, in contrast to other dispersion compensation devices, optical APF’s can correct any order of dispersion [2].

Optical all-pass filters have been implemented using side-coupled ring resonators [23], optical thin-film filters [24], or Gires-Tournois interferometers [4, 6]. Recent
research has shown that As$_2$S$_3$ rings can be coupled with Ti:LiNbO$_3$ waveguides to implement filtering functions by top coupling [18] and side coupling [19].

As hybrid devices which combines the As$_2$S$_3$ and LiNbO$_3$, their ring structures can be improved by doping Er in the coupling region and pumped by 1480nm laser to bring optical gain to compensate the round trip propagation losses which makes the rings lossless and have further potential applications.

1.3. Organization of the dissertation

After the background introduction of Chapter I, Chapter II gives the theoretical knowledge used in the following chapters. The electromagnetic theory and three numerical solvers have been reviewed first. Then the modeling of the optical waveguides, the feed-back resonator theory, electro-optical effect, the multilayer and Bragg grating reflectors have been introduced respectively.

In Chapter III, the simulations of the optical devices have been discussed. These devices include: titanium diffused waveguides; As$_2$S$_3$ assisted Er:Ti:LiNbO$_3$ waveguides; As$_2$S$_3$ rings on top of the Ti: LiNbO$_3$ waveguides; electrical optical devices; multilayer and Bragg reflectors. The results of simulations guide us on the device structure design and fabrication parameter settings.

In Chapter IV, the fabrication processes of three optical devices are introduced: As$_2$S$_3$ waveguide assisted Er:Ti:LiNbO$_3$, As$_2$S$_3$ ring on Er:Ti:LiNbO$_3$ and Er:Ti:LiNbO$_3$ cavity. Several experimental skills and recipes are discussed.
In Chapter V, the experimental results on fabricated waveguides in Chapter IV have been presented. Details of the measurement setup are revealed. Then in Chapter V, the dissertation is concluded and the prospect of the future work.
CHAPTER II
THEORETICAL REVIEW

2.1. Electromagnetic theory and waveguide mode solving

2.1.1. Electromagnetic theory

Classical electrodynamics theory can describe the electromagnetic phenomena accurately when quantum and relativistic effects are negligible. The properties of the optical wave or any other electromagnetic waves, including their excitation, propagation and interaction with media are governed by Maxwell’s equations. Maxwell’s equations in differential form are shown in equation to (2.1)–(2.4) [25].

\[ \nabla \cdot \mathbf{D} = \rho \]  
\[ \nabla \cdot \mathbf{B} = 0 \]  
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]  

where \( \mathbf{D} \) is the electric displacement (or electric flux density) vector, \( \mathbf{B} \) is magnetic flux density (or magnetic displacement) vector. \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic field vectors. \( \rho \) is the total free charge density. \( \mathbf{J} \) is the total current density vector.

The equations (2.1) and (2.2) are Gauss's law for electrics and Gauss's law for magnetism. They describe the normal components of the fields emanate from charges. Equations (2.3) and (2.4), which are the Faraday’s Law and Ampere’s Law, describe how the tangential components of the fields emanate from the flux changes.
The constitutive relations that represent the interactions between the electric, magnetic fields and the media are in (2.5) and (2.6):

\[ D = \varepsilon_0 E + P = \varepsilon_0 \varepsilon_r E = \varepsilon E \]  \hspace{1cm} (2.5)

\[ B = \mu_0 (H + M) = \mu_0 \mu_r H = \mu H \]  \hspace{1cm} (2.6)

where \( \varepsilon_0 \) is the permittivity and \( \mu_0 \) is the permeability of free space. \( \varepsilon \) is permittivity and \( \mu \) is the permeability in the media. \( P \) and \( M \) are polarization and magnetization respectively. When the medium is anisotropic, \( \varepsilon_r \) becomes a tensor. If the coordinate system matches the orientation of the crystal principal axes,

\[ D = \varepsilon_0 \varepsilon_r E = \varepsilon_0 \begin{bmatrix} \varepsilon_{r,11} \\ \varepsilon_{r,22} \\ \varepsilon_{r,33} \end{bmatrix} E \]  \hspace{1cm} (2.7)

The propagation speed of the light in the medium is characterized by the refractive index \( n \) and the relative permittivity \( \varepsilon_r \) (\( \mu_r \) is usually equals to 1).

\[ n = \frac{c}{v} = \frac{\sqrt{\varepsilon \mu}}{\sqrt{\varepsilon_0 \mu_0}} = \sqrt{\varepsilon_r} \]  \hspace{1cm} (2.8)

There is Ohm’s law in conductive materials:

\[ J = \sigma E \]  \hspace{1cm} (2.9)

In vacuum or isotropic medium, where no free charges and no conductive currents exist, those equations will lead the Wave Equations.

Take the curl of (2.3), and use the vector identity \( \nabla \times \nabla \times E = \nabla (\nabla \cdot E) - \nabla^2 E \). Bring in (2.2) which yield \( \nabla \cdot E = 0 \) then we have

\[ -\nabla^2 E = -\mu \frac{\partial}{\partial t} (\nabla \times H) \]  \hspace{1cm} (2.10)
Use (2.4) to substitute the $\nabla \times \mathbf{H}$ part above and we have

$$\nabla^2 \mathbf{E} - \frac{\varepsilon_r \mu_r}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0$$  \hspace{1cm} (2.11)$$

where $c$ is the speed of light in vacuum,

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 2.99794 \times 10^8 \text{ m/s} \hspace{1cm} (2.12)$$

Follow the similar process, we can get

$$\nabla^2 \mathbf{H} - \frac{\varepsilon_r \mu_r}{c^2} \frac{\partial^2 \mathbf{H}}{\partial t^2} = 0$$  \hspace{1cm} (2.13)$$

The solutions of these wave equations (2.11) and (2.13) are all kinds of wave expressions. The planar wave is the widely used:

$$\mathbf{E} = A \exp[i(k \cdot r - \omega t)]$$  \hspace{1cm} (2.14)$$

where $k$ is the wave number:

$$k = \frac{2\pi}{\lambda}$$  \hspace{1cm} (2.15)$$

When light propagation from one medium to another, the boundary conditions must to be considered:

$$\begin{cases} 
    n \cdot (\mathbf{D}_1 - \mathbf{D}_2) = 0 \\
    n \cdot (\mathbf{B}_1 - \mathbf{B}_2) = 0 \\
    n \times (\mathbf{E}_1 - \mathbf{E}_2) = 0 \\
    n \times (\mathbf{H}_1 - \mathbf{H}_2) = 0
\end{cases}$$  \hspace{1cm} (2.16)$$

They are directly derived from the integrated form of (2.1) ~ (2.4) by integration around the infinite small volume or area across the interface. Using the boundary conditions, the equations for refraction and reflection can be derived.
In Fig. 4, \( E = A \exp[i(k \cdot r - \omega t)] \) is the incident wave, \( E = A \exp[i(k \cdot r - \omega t)] \) is the reflected wave and \( E = A \exp[i(k \cdot r - \omega t)] \) is the refracted wave.

By using the boundary condition \( n \cdot (\mathbf{D}_1 - \mathbf{D}_2) = 0 \), the following equations can be obtained:

\[
k_1 \cdot r = k_2 \cdot r = k_3 \cdot r \quad (2.17)
\]

Considering the direction of \( r \) is normal to the interface, (2.17) can be transformed:

\[
\theta_1 = \theta_2 \quad (2.18)
\]

\[
n_1 \sin(\theta_1) = n_2 \sin(\theta_3) \quad (2.19)
\]

The reflected light has the same angle as incident light in (2.18), and the refracted light follows Snell’s Law in (2.19).
From (2.19), if the light incident from higher index medium to the lower index medium \((n_1 > n_2)\) and \(\theta_i\) is large enough \(\theta_i > \theta_c = \sin^{-1}(n_2/n_1)\), \(\theta_c\) is called critical angle), \(\theta_i\) could be a complex number which means the light cannot enter medium two. It is called total internal reflection (Fig. 5) and it is the principle of light confinement properties of the dielectric waveguides.

![Fig. 5. Total internal reflection.](image)

Integrated waveguides, serving as an optical interconnection, guide light by total internal reflection.

### 2.1.2. Numerical solvers

A comprehensively and accurately understanding of the characteristics of the propagating light inside the waveguides requires both analytical expressions and numerical simulations. The analytical expressions have been intensively investigated. The 2D waveguide which is composed of a higher index layer sandwiched by two low
index cladding layers has the analytical equations which can calculate the eigenvalue and then the effective index. The calculations for 3D waveguide calculation can be more difficult since the cross sections of them are more complicated. The major methods are Marcatilis’s method for strong guided (high index contrast) rectangular waveguides such as channel waveguides and effective index method for weak guided such as diffused waveguides.

However, for waveguides with irregular cross sections or variational cross sections along the direction of propagation, these analytical expressions are helpless. Then the numerical solvers became attractive and powerful.

The numerical methods digitalize the index profile and mode profile on the cross section of the waveguide by dividing the whole waveguide into mesh grid points. All the data such as refractive index or amplitude densities are represented by the values on these discrete points. Then the solvers evolve the Maxwell’s difference equation to difference equations based on their own simplification and assumptions. With the boundary conditions and initial conditions, the eigenvalues or the effective index can be “guess out” by specific convergent algorithms. Not only the eigenvalues, but also the mode profiles, beam widths, the dispersions, the confinement factors, etc. All the optical information about the waveguides can be calculated. The accuracy depends on the resolution of the mesh points. However, more points bring more calculation time. So the accuracy and calculation time can be a trade-off although several skills have been brought into the convergent algorithms to speed up the calculation.
Also, the numerical solvers can simulate the beam propagation through varying waveguides which makes them capable of simulating “two by two” coupler, Mach-Zehnder Interferometer, etc. Moreover, with add-in Electro-optic parameters, they can simulate the EO modulator. The Film Mode Matching (FMM) solver [26], Finite Different Mode (FDM) solver [27] and Finite Element method (FEM) solver are the most useful solvers.

2.2. Optical waveguides modeling

2.2.1. Modeling of the Ti: LiNbO₃

The simulation by computer software with numerical methods is becoming more and more powerful. Before setting up the simulation work chapter III, the modeling of the titanium diffused waveguides is discussed here. The lithium niobate substrate discussed in this chapter is x-cut, y-propagation.

The diffusion model includes two groups of parameters: diffusion coefficients and index change coefficients. The diffusion coefficients describe how deep the dopants can diffuse through the substrate in a specific time period. And the index change coefficients describe how large the index will change (usually increase) from to the concentration of the dopant.

The overall index is the sum of the bulk index \( n_o \) or \( n_e \) and the diffusion induced change index change \( \Delta n_i \) [28],

\[
n_i(\lambda, x, y) = n_i(\lambda) + \Delta n_i(\lambda, x, y) \quad i = o, e
\] (2.20)
The ordinary and extraordinary bulk indices (at 25°C) of congruent lithium niobate can be expressed by Sellmeier’s dispersion equations ($\lambda$ in $\mu$m)

\[
n_o^2 = 4.9048 - \frac{0.11768}{0.0475 - \lambda^2} - 0.027169\lambda^2
\]

\[
n_e^2 = 4.582 - \frac{0.099169}{0.044432 - \lambda^2} - 0.02195\lambda^2
\]

(2.21) and (2.22) originate from [29], and the parameters were updated in [30]. (2.21) and (2.22) give us: $n_o = 2.2112$, $n_e = 2.1381$ at $\lambda = 1550$nm. Compare to more precise $n_e$ from [31]: $n_e = 2.137880$.

The Relative error is $(2.138064-2.137880)/2.137880*100\% = 0.0086\%$ which can be neglected.

Then we can discuss the diffusion induced index change: $\Delta n_i$. The $\Delta n_i$ comes from the in-diffused Ti$^{4+}$. The diffusion process must be done in wet O$_2$ or wet air ambient to suppress out-diffusion of Li$_2$O which will induce another $\Delta n_e$. Otherwise this additional $\Delta n_e$ throughout the lithium niobate surface will make strip waveguide lose its light confinement in the direction perpendicular to the waveguide and more like be a planer waveguide and induce high order-TE mode [10].

From [28],

\[
\Delta n_i(\lambda, x, y) = d_i(\lambda)h_i(x, y), \quad i = o, e
\]

$d_i(\lambda)$ is called dispersion factor and it describes the wavelength dependence.

\[
d_o(\lambda) = \frac{0.67\lambda^2}{\lambda^2 - 0.13}, \quad d_e(\lambda) = \frac{0.839\lambda^2}{\lambda^2 - 0.0645}
\]
\( h_i(x, y) \) is Ti\(^{4+} \) concentration dependent function.

\[
h_i(x, y) = [F_i c(x, y)]^{\gamma_i} \quad i = o, e
\] (2.25)

where the distribution constants are \( F_o = 1.3 \times 10^{-25} \text{cm}^3 \), \( F_e = 1.2 \times 10^{-23} \text{cm}^3 \). And the distribution power factors are \( \gamma_o = 0.55 \), \( \gamma_e = 1.00 \).

For titanium diffused waveguide, the typical diffusion temperature is at 1025 °C, the titanium thickness is around 100 nm and the diffusion time is around 10 hours. The waveguide formed by this process can guide mode which matches best to the fiber mode and result in lowest coupling loss. From [32], \( \Delta n_e \approx 0.015, \Delta n_o \approx 0.007 \).

Now we have the relation between Ti\(^{4+} \) concentration and the index change, and still we need to know the Ti\(^{4+} \) concentration.

The diffused Ti\(^{4+} \) concentration Profile was created by two-steps high temperature diffusion process: predeposition and drive-in.

(a) Pre-deposition (\( t \leq t_e \)):

The depletion time \( t_e \) is the time when titanium strip totally diffuses into the substrate. From [33]:

\[
t_e = \left( \frac{\rho N_A \tau}{M_{rel} 2c_0} \right)^2 \frac{\pi}{D_v}
\] (2.26)

where \( \rho \) is the density, \( N_A \) the Avogadro’s numer, \( \tau \) the initial Ti thickness and \( M_{rel} \) the relative mass of the Ti. \( D_v \) is the vertical diffusion coefficient. By choosing the values below, the titanium depletion time can be calculated in Table I. The normal titanium waveguide diffusion time is about two times larger than the depletion time. So
they are in the drive-in region. The values are listed: \( \rho = 4.5g/cm^3 \), 
\( N_d = 6.022e23 \text{ mol}^{-1} \), \( M_{nd} = 47.9 \), \( D_v = 1.45e^{-12}cm^2/s \) \((\text{at } 1025°C)\), \( C_o = 3.0e21 \text{ cm}^3 \)

<table>
<thead>
<tr>
<th>Ti Thickness(A)</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depletion Time(hr)</td>
<td>1.9</td>
<td>2.6</td>
<td>3.4</td>
<td>4.4</td>
<td>5.37</td>
<td>6.5</td>
<td>7.73</td>
<td>9.08</td>
<td>10.5</td>
<td>12.1</td>
</tr>
</tbody>
</table>

In the time regime of predeposition, the surface concentration is a constant limited by the solubility of Ti\(^{4+}\) in LiNbO\(_3\) \((c_s = 5.67e22 \text{ cm}^{-3}\)) , the profile is an error function [34].

TM mode will have great loss in this time range. So our diffusion time is usually longer than \( t_e \) to make the TM mode loss lower.

(b) Drive-in: \((t > t_e)\)

In this part, all the Ti\(^{4+}\) ions have been diffused into the surface and the total amount of Ti\(^{4+}\) is a constant. The profile becomes a Gaussian function with a decreasing surface concentration.

TE, TM modes will have closer loss in this regime.

Although the relation between the technological procedure and the waveguide characteristics has not yet been established in a conclusive manner, the analytical expression (2.27) which separate \( x \) and \( y \) dependences has been widely accepted [28].
\[ c(x, y) = c_0 f(y) g(x) \]  

(2.27)

where

\[ c_0 = \frac{c_m \tau}{(\sqrt{\pi} D_v)}, c_m = \left( \frac{\rho}{M_{\text{atom}}} \right) N_A \]  

(2.28)

\[ f(y) = \exp\left(-\frac{y^2}{D_v}\right) \]  

(2.29)

\[ g(x) = \frac{\text{erf}\left[\frac{w}{2D_h} (1 + \frac{2x}{w})\right] + \text{erf}\left[\frac{w}{2D_h} (1 - \frac{2x}{w})\right]}{2} \]  

(2.30)

where \( w \) and \( \tau \) are the titanium strip width and thickness before diffusion. \( \rho \) is the bulk density of titanium, \( G \) is the atomic weight of titanium. \( D_v \) is vertical length and \( D_h \) the horizontal diffusion length.

The Arhenius relation from [33],

\[ D_v = 2\sqrt{tD_v^0 \exp\left(-\frac{E_v^0}{kT}\right)} \]  

(2.31)

\[ D_h = 2\sqrt{tD_h^0 \exp\left(-\frac{E_h^0}{kT}\right)} \]  

(2.32)

where \( t \) is the diffusion time, \( D_v^0 \) and \( D_h^0 \) are the horizontal and vertical diffusivities. \( E_v^0 \) and \( E_h^0 \) are the temperature dependence parameters (activation energy). \( k \) is the Boltzmann constant, and \( T \) is the temperature.

Some papers define \(-E_{0b} / kT\) as \(-T_0 / T\). A lot of papers give their experimental data. [11] gives the diffusion values close to our experimental data at \( T=1025^\circ C \):

After comparison with experiment results in Chapter III, the three basic parameters have been fitted:
\[
D^0_r = 0.0199 \text{cm}^2 / \text{s}, \text{(Diffusivity on Ordinary axis)}
\]
\[
D^0_h = 0.0289 \times 10^{-12} \text{cm}^2 / \text{s}, \text{(Diffusivity on Extraordinary axis)}
\]
\[
T_o = T_e = 3.03 \times 10^4 K
\]

Also, \(d_e(\lambda)\) and \(d_o(\lambda)\) in (2.24) have been inserted in correction factors: 1.7 and 1.49 respectively.

\[
d_e(\lambda) = \frac{0.839 \lambda^2}{\lambda^2 - 0.0645} \times 1.7, \quad d_o(\lambda) = \frac{0.67 \lambda^2}{\lambda^2 - 0.13} \times 1.49
\]  

The parameters in (2.33) were fitted from the comparison between measured and simulated mode width data in section 3.1.1. The calculation can be performed by Matlab and the code is in APPENDIX A.

(c) Intermediate, \(t \approx t_e\),

The diffusion profile is in a state between error function and Gaussian function. And the surface concentration is getting lower than solubility. But it is not the value as \(c_0\) from (3.9). This still needs future discussion.

After discussing the model of titanium diffused waveguides, the simulation can be performed in Chapter III.

\[\text{2.2.2. Modeling of the Er diffusion in LiNbO}_3\]

The erbium diffusion in LiNbO3 is treated as planar in-diffusion.

\[
c(y) = \hat{C}_0 \exp\left(\frac{-y^2}{4Dt}\right)
\]

\[
\hat{C}_0 = \tau C_0 / \sqrt{\pi Dt}
\]
\( \hat{C}_0 \) is the surface concentration. \( D \) is the diffusion coefficient and \( t \) is the diffusion time. The Er profile is described by (2.35), only if the diffusion time larger than depletion time [35].

\[
t_{d} = \left( \frac{\rho N_A \tau}{M_{rel} 2c_0} \right)^2 \frac{\pi}{Dv}
\]

where \( \rho \) is the density, \( N_A \) the Avogadro’s numer, \( M_{rel} \) the relative mass of the Er and \( \tau \) the initial Er thickness. \( Dv \) is the vertical diffusion coefficient. The values are:

\[
\rho = 9.066 g/cm^3, \quad N_A = 6.022e23 \text{ mol}^{-1}, \quad M_{rel} = 167.259 g/mol
\]

\[
Dv = 0.025 \text{um}^2/h = 2.5 \times 10^{-10} \text{cm}^2/h \text{ (at 1100°C)} \quad [35].
\]

The values of \( C_0 \) are not consistent. In [35], figure number 4 gives \( C_0^1 = 2e20 \text{ cm}^3 \) but figure number 2 gives \( C_0^2 = 4e20 \text{ cm}^3 \).

<table>
<thead>
<tr>
<th>Er Thickness(nm)</th>
<th>10</th>
<th>11</th>
<th>15</th>
<th>19</th>
<th>21</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depletion Time(hr)(1)</td>
<td>83.6</td>
<td>101</td>
<td>188</td>
<td>302</td>
<td>369</td>
<td>442</td>
<td>523</td>
</tr>
<tr>
<td>Depletion Time(hr)(2)</td>
<td>20.9</td>
<td>25.3</td>
<td>47.1</td>
<td>75.5</td>
<td>92</td>
<td>111</td>
<td>131</td>
</tr>
</tbody>
</table>

In the Table II, (2) is more close to the experiment in our laboratory.

The Er diffusion time should be larger than the depletion time to let the Er totally diffuse into the LN crystal.
The conversion between mol% to cm\(^{-3}\) is shown below. For example, 0.5 mol% of Er in LN was converted to density of Er in LN. The molar weight of Er and LiNbO\(_3\) are 167.259 g/mol and 147.846 g/mol. Density of LiNbO\(_3\) is 4.65 g/cm\(^3\), then the density of Er in LiNbO\(_3\) is 
\[
\rho = \frac{4.65}{147.846} \times 0.5\% \times N_A = 9.47 \times 10^{19} \text{ cm}^{-3}.
\]

### 2.2.3. Modeling of the Er gain

The gain of the amplifier is a function of the overlap between the Er profile and optical mode. In the two-level model, the steady state propagation equation describing the signal power evolution in the optical amplifier is given by \([36, 37]\),

\[
\frac{\partial P_s(z)}{\partial z} = (\gamma_{21} - \gamma_{12}) P_s(z) - \alpha P_s(z) \tag{2.38}
\]

\[
\gamma_{21} = N_2(z) \int_A \Psi_s(x,y) \sigma^e \rho \text{Er}(x,y) \, dx \, dy \tag{2.39}
\]

\[
\gamma_{12} = N_1(z) \int_A \Psi_s(x,y) \sigma^a \rho \text{Er}(x,y) \, dx \, dy \tag{2.40}
\]

\[
\int_A \Psi_s(x,y) \, dx \, dy = 1 \tag{2.41}
\]

where \(P_s\) is the signal power, \(\Psi_s\) is the normalized mode distribution as shown in (2.41). \(\gamma_{21}\) and \(\gamma_{12}\) are expressed by (2.39) and (2.40). \(\rho\) is the density of Er atoms at the LiNbO\(_3\) surface, \(\text{Er}(x,y)\) is the normalized diffused Er profile, where the maximum of \(\text{Er}(x,y) = 1\). \(\sigma^e\) and \(\sigma^a\) are the cross sections for stimulated emission and absorption at signal wavelength. \(N_2(z)\) and \(N_1(z)\) are the fraction of atoms per unit length in the excited state and ground state \((N_2(z) + N_1(z) = 1, [37])\) which are determined by the pump efficiency.
Here the amplified spontaneous emission (ASE) noise is ignored since the gain is small. We assumed that the pump power is high enough (>20dBm) to maximize the population inversion of the Er atoms so that the gain is uniform along the waveguide. Substituting (2.39)~(2.41) into (2.38) becomes:

\[
\frac{\partial P_s(z)}{\partial z} / P_s(z) = \rho \Gamma \left[ (\sigma_s^e + \sigma_s^a)N_2(z) - \sigma_s^a \right] - \alpha_s \\
\Gamma = \iiint \Psi_s(x,y)Er(x,y)dxdy 
\]

(2.42)

(2.43)

where \(\Gamma\) expressed by (2.43) is the overlap between the normalized signal mode \(\Psi_s\), and the Er profile \(Er(x,y)\), and \(\alpha_s\) is the propagation loss.

The optical gain (dB per unit length) can be expressed by inserting the conversion factor \(10\log(e)\) into (2.42) [37]. The propagation gain (gain per unit length) is defined as the gain relative to the non Er doped waveguide, which has loss \(\alpha_s\), as follows:

\[
Gain(dB/l) = 10\log(e)\rho \Gamma \left[ (\sigma_s^e + \sigma_s^a)N_2(z) - \sigma_s^a \right] 
\]

(2.44)

So the propagation gain is proportional to the overlap between the signal mode and Er profile.

### 2.3. Ring resonator theory

My research is focus on the gain improvement in the loop of the feedback filter. Our group already made device shown in Fig. 6(a) by integrating As\(_2\)S\(_3\) ring on top of the Ti:LiNbO\(_3\) [18, 19]. Measured amplitude is shown in Fig. 6(b).
The ring structure can be modeled by a simple 2by2 coupler and 1 feed back loop in Fig. 7. The through port has coupling ratio $\rho = \sqrt{1-k}$ and the cross port has coupling ratio $-j\sqrt{k}$. The feedback loop’s delay $e^{-jwt}$ can be expressed by $z^{-1}$ as the unit delay time. And the round trip loss is expressed by $\gamma$. So the whole system can be analysis by $z$-transform. The output of the ring can be expressed by $Y(z) = [\rho - k\gamma z^{-1} - \rho k\gamma^2 z^{-2} - ...]X(z)$. 

Fig. 6. As$_2$S$_3$ ring side coupled to Ti:LiNbO$_3$ waveguide: (a) Schematic structure; (b) SEM image of the fabricated ring device: side-coupling region.
Fig. 7. Transmission and group delay response of the ring structure.

So the transfer function \( H(z) = \frac{\rho - \gamma z^{-1}}{1 - \rho z^{-1}} \). The amplitude is \( 20 \log \left| \frac{\rho - \gamma z^{-1}}{1 - \rho z^{-1}} \right| \) and the phase is \( \arg \left( \frac{\rho - \gamma z^{-1}}{1 - \rho z^{-1}} \right) \).

The power transmission is

\[
T = H^*H = \frac{c - \gamma e^{-j\omega t}}{1 - c\gamma e^{-j\omega t}} \cdot \frac{c - \gamma e^{j\omega t}}{1 - c\gamma e^{j\omega t}} = \frac{c^2 - 2\gamma c \cos(\omega t) + \gamma^2}{1 - 2\gamma c \cos(\omega t) + c^2 \gamma^2}, c = \rho
\]

(2.45)

\[
T_{\text{min}} = \left( \frac{c - \gamma}{1 - c\gamma} \right)^2, \omega t = 0, \text{on resonance}
\]

(2.46)

\[
T_{\text{max}} = \left( \frac{c + \gamma}{1 + c\gamma} \right)^2, \omega t = \pi, \text{off resonance}
\]

(2.47)
Extinction ratio of the ring response,

\[
\frac{T_{\text{max}}}{T_{\text{min}}} = \left(\frac{c + \gamma}{1 + c\gamma}\right)^2 \left(\frac{1 - c\gamma}{c - \gamma}\right)^2
\]  

(2.48)

When \( c = \gamma \), from (2.19), we have \( T_{\text{min}} = 0 \). This is the critical coupling.

Our goal is to make a filter with sharp amplitude response as shown in Fig. 8, \( \rho = 0.98 \).

Fig. 8. Normalized amplitude response, \( \rho = 0.98 \).

Our goal is to make a filter with sharp amplitude response as shown in Fig. 8, \( \gamma \) is swept at 0.5, 0.9, 0.99 while \( \rho = 0.98 \). In Fig. 9, \( \rho \) is swept at 0, 0.5, 0.9 while \( \gamma = 0.5 dB \). The simulations show that the sharp response requires that both \( \rho \) and \( \gamma \) close to 1.
2.4. Electro-optical effect

The linear Electro-optic effect (or Pockels effect) produces refractive index change in certain types of crystals (such as LiNbO$_3$) induced by a constant or varying electric field. This index change is proportional to the field in Pockels effect whereas in Kerr effect it is quadratic in the field.
The index ellipsoid is used to describe the anisotropic property of these materials (Fig. 10). And the electro-optical properties are observed in ferroelectric crystals. In those crystals, the refractive index is dependent on crystal structure such that they exhibit optical anisotropy, i.e., the refractive index changes when varying the propagation direction. An index ellipsoid is introduced for such anisotropic material to determine the refractive index (Fig. 10). When the principal axes of the index ellipsoid coincide with x, y and z, the ellipsoid can be expressed by (2.49)

$$\frac{x^2}{n_x} + \frac{y^2}{n_y} + \frac{z^2}{n_z} = 1 \quad (2.49)$$

or in terms of relative permittivity,

$$\frac{X^2}{\varepsilon_{11}} + \frac{Y^2}{\varepsilon_{22}} + \frac{Z^2}{\varepsilon_{33}} = 1 \quad (2.50)$$

where $n_i^2 = \varepsilon_{ij}$. Re-arrange it by using the impermeability tensor:

$$B_{11}X^2 + B_{22}Y^2 + B_{33}Z^2 = 1 \quad (2.51)$$
where \( B = \frac{1}{\varepsilon_r} = \frac{1}{n^2} \).

After the application of the electric field, the induced index ellipsoid is no longer aligned with the coordinate system and the off diagonal terms appears,

\[
B'_{11}X^2 + B'_{22}Y^2 + B'_{33}Z^2 + 2B'_{23}YZ + 2B'_{31}ZX + 2B'_{12}XY = 1
\]

(2.52)

Renaming the coefficients for convenience,

\[
B'_iX^2 + B'_iY^2 + B'_iZ^2 + 2B'_iYZ + 2B'_iZX + 2B'_iXY = 1
\]

(2.53)

The difference of the index ellipsoids with and without electric field,

\[
\Delta B_i = B'_i - B_i \equiv \Delta \left( \frac{1}{n^2} \right) = \sum_{i=1,2,3} r_i E_j
\]

(2.54)

Then rewrite it explicitly,

\[
\begin{pmatrix}
\Delta \left( \frac{1}{n_1^2} \right) \\
\Delta \left( \frac{1}{n_2^2} \right) \\
\Delta \left( \frac{1}{n_3^2} \right) \\
\Delta \left( \frac{1}{n_4^2} \right) \\
\Delta \left( \frac{1}{n_5^2} \right) \\
\Delta \left( \frac{1}{n_6^2} \right)
\end{pmatrix} =
\begin{pmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33} \\
r_{41} & r_{42} & r_{43} \\
r_{51} & r_{52} & r_{53} \\
r_{61} & r_{62} & r_{63}
\end{pmatrix}
\begin{pmatrix}
E_1 \\
E_2 \\
E_3
\end{pmatrix}
\]

(2.55)

The electro-optical tensor of LiNbO$_3$ (trigonal 3m crystal class) has the format
$$r_{ij} = \begin{pmatrix}
0 & -r_{22} & r_{13} \\
0 & r_{22} & r_{13} \\
0 & 0 & r_{33} \\
0 & r_{51} & 0 \\
r_{51} & 0 & 0 \\
-r_{22} & 0 & 0
\end{pmatrix}$$ (2.56)

While the values at the wavelength of 632.8 nm are,

$$\begin{cases}
r_{22} = 3.4 \times 10^{-12} m/V \\
r_{13} = 8.6 \times 10^{-12} m/V \\
r_{33} = 30.8 \times 10^{-12} m/V \\
r_{51} = 28 \times 10^{-12} m/V
\end{cases}$$ (2.57)

By using the small argument binomial expansion, we can relate the $\Delta n_i$ directly to the electric field instead of the $\Delta \left( \frac{1}{n_i} \right)$,

$$\Delta n_i = -\frac{1}{2} n_i^3 \sum_{j=1}^{3} r_{ij} E_j$$ for $i = 1, 2, ..., 6$ (2.58)

So the applied electric field component $E_j$ changes the refractive indices linearly.

2.5. Multilayer and Bragg grating reflectors

2.5.1. Multilayer reflector

The multilayer dielectric films which consist of a stack of quarter-wave dielectric layers of alternate high and low index have large reflectivity and low loss. It is the best choice to be the nearly 100% mirrors of the cavities.
The following theory has two simple assumptions: (1) Normal incidence; (2) Negligible material absorption [38]. Several definitions are bought in first and then the derivations are performed to get the frequency response of the multilayer reflectors.

(a) Refractive index and admittance

\[ N = n - ik = c / \nu = \sqrt{\varepsilon_r} \]  

\( N \) is the complex refractive index, \( n \) is the real refractive index (or often simply refractive index), and \( k \) is the extinction coefficient. \( k \) is related with the absorption coefficient \( \alpha = 4\pi k / \lambda \). The absorption is negligible for the dielectric materials As\(_2\)S\(_3\) and SiO\(_2\). \( c \) and \( \nu \) are the velocity of light in free space and in medium. \( \varepsilon_r \) is the relative dielectric permittivity.

The optical admittance is defined by the ratio of the magnetic and electric fields:

\[ y = \eta = H / E = \sqrt{\varepsilon / \mu_0} \]  

\( y \) is complex when the medium has absorption. In free space, \( y \) is real and is denoted by \( y_0 = \sqrt{\varepsilon_0 / \mu_0} = 2.6544 \times 10^{-3} \, \text{S} \).

In medium,

\[ y = Ny_0 \]  

\( y \) is complex when the medium has absorption. In free space, \( y \) is real and is denoted by \( y_0 = \sqrt{\varepsilon_0 / \mu_0} = 2.6544 \times 10^{-3} \, \text{S} \).

The irradiance of the light is defined as the mean rate of the flow of the energy per unit area carried by the light wave. It is given by

\[ I = \frac{1}{2} \text{Re}(EH^*) = \frac{1}{2} ny_0 EE^* \]
(b) Reflection of a boundary

The incident beam is shooting from air \((n_0)\) to substrate \((n_1)\). And the continuities of the electric and magnetic tangential components are:

1. Electric tangential component continuous across the boundary

\[ \varepsilon_i + \varepsilon_r = \varepsilon_t \]  

(2.63)

2. Magnetic tangential component continuous across the boundary

\[ y_0\varepsilon_i - y_0\varepsilon_r = y_1\varepsilon_r \]  

(2.64)

Eliminating \(\varepsilon_i\) and \(\varepsilon_r\), we obtain the amplitude coefficients:

Reflection:

\[ \rho = \frac{\varepsilon_r}{\varepsilon_i} = \frac{y_0 - y_1}{y_0 + y_1} = \frac{n_0 - n_1}{n_0 + n_1} \]  

(2.65)

Transmission:

\[ \tau = \frac{\varepsilon_r}{\varepsilon_i} = \frac{2y_0}{y_0 + y_1} = \frac{2n_0}{n_0 + n_1} \]  

(2.66)

Power reflection:

\[ R = \rho^2 = \left(\frac{n_0 - n_1}{n_0 + n_1}\right)^2 \]  

(2.67)

Power transmission:

\[ T = \frac{y_1}{y_0}\tau^2 = \frac{4n_0n_1}{(n_0 + n_1)^2} \]  

(2.68)

(c) Reflection of a thin film and multilayer thin film

A single film has two interfaces, with air and with substrate. Use the same boundary conditions discussed above and combine all the multi-reflection beams with two positive-going and two negative-going waves in the film, four equations can relate the beams in the air and the beams in the substrate. A phase factor \(\exp(i\delta)\) is introduced to relate the phase change between two interfaces to simplify the notations,
\[
\delta = 2\pi N_i d \cos(\vartheta_i) / \lambda
\]  
(2.69)

\[N_i\] is the index of the film, \(d\) is the thickness of the film, \(\vartheta_i\) is the angle of the beam in the film (equals to zero in this discussion), \(\lambda\) is the wavelength.

Finally, a matrix can be derived to relate the amplitude of tangential components of \(E\) and \(H\) (subscript “a” is the 1\(^{\text{st}}\) interface between air and the film and subscript “b” is the 2\(^{\text{nd}}\) interface between film and substrate):

\[
\begin{bmatrix}
E_a \\
H_a
\end{bmatrix} = \begin{bmatrix}
\cos \delta & (i \sin \delta) / \eta_i \\
in_i \eta_i & \cos \delta
\end{bmatrix} \begin{bmatrix}
E_b \\
H_b
\end{bmatrix}
\]  
(2.70)

Normalize it to \(E_b\),

\[
\begin{bmatrix}
E_a / E_b \\
H_a / E_b
\end{bmatrix} = \begin{bmatrix}
B \\
C
\end{bmatrix} = \begin{bmatrix}
\cos \delta & (i \sin \delta) / \eta_i \\
in_i \eta_i & \cos \delta
\end{bmatrix} \begin{bmatrix} 1 \\
\eta_2
\end{bmatrix}
\]  
(2.71)

This equation can calculate the admittance \(y = \frac{H_a}{E_a} = \frac{C}{B}\) of the overall combination of the film and substrate and then the reflection:

\[
\rho = \frac{\eta_0 - y}{\eta_0 + y}
\]  
(2.72)

\[
R = \left( \frac{\eta_0 - y}{\eta_0 + y} \right) \eta_0 - y
\]  
(2.73)

For multilayer films, the calculation can be simplified by similar matrix form:

\[
\begin{bmatrix}
B \\
C
\end{bmatrix} = \prod_{r=1}^{a} \begin{bmatrix}
\cos \delta_r & (i \sin \delta_r) / \eta_r \\
in_r \eta_r & \cos \delta_r
\end{bmatrix} \begin{bmatrix} 1 \\
\eta_{sub}
\end{bmatrix}
\]  
(2.74)

where
\[
\delta_r = \frac{2\pi N_r d_r \cos(\vartheta)}{\lambda} \quad \text{our case} \Rightarrow \delta_r = \frac{2\pi n_r d_r}{\lambda}
\] (2.75)

Then the admittance is

\[
y = \frac{C}{B}
\] (2.76)

Amplitude Reflection:

\[
\rho = \frac{\eta_0 - y}{\eta_0 + y}
\] (2.77)

Intensity Reflection:

\[
R = \begin{pmatrix}
\eta_0 - y \\
\eta_0 + y
\end{pmatrix} \begin{pmatrix}
\eta_0 - y \\
\eta_0 + y
\end{pmatrix}^*
\] (2.78)

Phase change:

\[
\text{Phase}(\rho) = \arg \left( \frac{\eta_0 - y}{\eta_0 + y} \right)
\] (2.79)

(d) Quarter-wave dielectric layers

If the films have quarter-wave thickness, and the multilayer consists of an odd number of layers with high-index layers on the outside (p+1 layers of high index material and p layers of low index material), the equations in the previous section can be simplified by,

\[
\delta_r = \frac{\lambda}{2}
\] (2.80)

The matrix becomes,

\[
\pm \begin{bmatrix}
0 & i/\eta \\
i\eta & 0
\end{bmatrix}
\] (2.81)
\[ y = \frac{n_H^{2p+2}}{n_I^{2p} n_{\text{sub}}} \]  

(2.82)

Reflectance:

\[ R = \left[ 1 - \frac{n_H^{2p+2} / (n_I^{2p} n_{\text{sub}})}{1 + n_H^{2p+2} / (n_I^{2p} n_{\text{sub}})} \right]^2 \approx 1 - 4 \frac{n_L^{2p} n_{\text{sub}}}{n_H^{2p+2}, \text{when} \frac{n_H^{2p+2}}{n_L^{2p} n_{\text{sub}}} > 1} \]  

(2.83)

Reflection Loss:

When \( R \approx 1, 4 \frac{n_L^{2p} n_{\text{sub}}}{n_H^{2p+2}} = x \approx 0, \)

\[ L_{dB} = 10 \log(R) = 10 \log(1 - x) \approx 4.343^*(-x) = -4.343^* 4 \frac{n_L^{2p} n_{\text{sub}}}{n_H^{2p+2}} \]  

(2.84)

Wavelength range:

\[ \Delta g = \frac{2}{\pi} \arcsin \left( \frac{n_H - n_I}{n_H + n_I} \right) \]  

(2.85)

2.5.2. Bragg grating reflector

The Bragg grating is a periodic perturbation of the refractive index along the length of the propagation. The first grating in fiber was demonstrated by Hill et al [39, 40] in 1978 by photo-induced refractivity.

Similar to the multilayer reflectors, the index of the Bragg grating through the propagation is a periodic structure, and the strongest interaction or mode-coupling occurs at the Bragg wavelength \( \lambda_B \),

\[ \lambda_B = 2n_{\text{eff}}\Lambda \]  

(2.86)

The \( n_{\text{eff}} \) is the modal index and the \( \Lambda \) is the grating period.
The grating filter characteristics can be modeled by several approaches [41-45].

The most important equations are listed since the detailed discussion is not necessary:

\[ \Delta \lambda = \left[ \frac{2\Delta n}{\pi} \right] \lambda_B \]  

(2.87)

where \( \Delta n \) is the variation in the refractive index.

The peak reflection is approximately given by,

\[ P_B(\lambda_B) \approx \text{tanh}^2 \left[ \frac{N\Delta n}{n_{\text{eff}}} \right] \]  

(2.88)

where \( N \) is the number of periodic variations.
CHAPTER III

SIMULATION*

3.1. Ti:LiNbO₃ waveguides

The simulation of the titanium (Ti) waveguides is mainly relied on the “mode solving” capability of the software. With the input refractive index profile at the cross sections of the waveguides, the computer software can solve the modes exist in the waveguides by numerical methods. We use the commercial software OptiBPM (from Optiwave) and FIMMWAVE (from Photo Design Ltd) to realize this work.

Before setting up the simulation, the modeling of the titanium diffused waveguides are discussed in Chapter II. In this chapter, we will use the model to simulate titanium diffused waveguides in lithium niobate.


Part of this chapter is reprinted with permission from "Gain improvement of Er-Ti:LiNbO₃ waveguide amplifier by an As2S3 overlay waveguide" by Xiaomin Song, Wee Chong Tan, William Timothy Snider, Xin Xia, and Christi K. Madsen, IEEE Photon. J., 3, 686-695, 2011, copyright 2011 by IEEE.
3.1.1. Titanium diffusion parameters

In chapter 2.2.1, the model of titanium diffused waveguide in lithium niobate has been discussed. But the parameters still need to be extract from the results measured from our own fabricated samples.

In Table III, the experimental and simulated mode width data have been compared. The experiment mode data came from the mode profile measurements which will be discussed in chapter V. The waveguide mode has horizontal width and vertical width. They are expressed in full width at half maximum (FWHM) and they all have been measured and simulated. In bottom part of this table, the simulated widths have been compared with the measured data and the variations have been listed beside them.

<table>
<thead>
<tr>
<th>Experimental Data</th>
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<td>Polari-</td>
<td>Ti thi-</td>
<td>D time</td>
<td>H_FWHM</td>
<td>V_FWHM</td>
<td>H/V</td>
</tr>
<tr>
<td>ID</td>
<td>zation</td>
<td>ckness(A)</td>
<td>(h)</td>
<td>(µm)</td>
<td>(µm)</td>
<td>Mode Index</td>
</tr>
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<td>TE</td>
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<td>5.3143</td>
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<td>1.37</td>
</tr>
<tr>
<td>RC39</td>
<td>TM</td>
<td>920</td>
<td>9.5</td>
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<td>7.2035</td>
<td>3.9145</td>
<td>1.84</td>
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<td>Polari-</td>
<td>Ti thi-</td>
<td>D time</td>
<td>H_FWHM</td>
<td>V_FWHM</td>
<td>H/V</td>
</tr>
<tr>
<td>ID</td>
<td>zation</td>
<td>ckness(A)</td>
<td>(h)</td>
<td>(µm)</td>
<td>(µm)</td>
<td>Mode Index</td>
</tr>
<tr>
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<td>TE</td>
<td>920</td>
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<td>5.5629</td>
<td>3.4437</td>
<td>(+4.57%)</td>
</tr>
<tr>
<td>RC39</td>
<td>TM</td>
<td>920</td>
<td>9.5</td>
<td>7.5497</td>
<td>4.6358</td>
<td>(-7.43%)</td>
</tr>
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<td>TE</td>
<td>950</td>
<td>9.5</td>
<td>5.5629</td>
<td>3.5762</td>
<td>(-4.27%)</td>
</tr>
<tr>
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<td>TM</td>
<td>950</td>
<td>9.5</td>
<td>7.5497</td>
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<td>(-4.45%)</td>
</tr>
<tr>
<td>RC58</td>
<td>TE</td>
<td>1290</td>
<td>13</td>
<td>5.5629</td>
<td>3.5762</td>
<td>(-1.70%)</td>
</tr>
<tr>
<td>RC58</td>
<td>TM</td>
<td>1290</td>
<td>13</td>
<td>7.5497</td>
<td>4.7682</td>
<td>(+4.69%)</td>
</tr>
</tbody>
</table>
The diffusion parameters in (2.33) and (2.34) were fitted from Table III to minimize the variation between the measurements and simulations.

3.1.2. Basic Ti:LiNbO₃ waveguide simulations

The simulation was performed by OptiBPM [46].

(a) Refractive index distributions

The refractive index distributions have been generated by inputting the waveguide dimensions along with the diffusion parameters: diffusivities (at specific temperature), diffusion time, titanium strip thickness and width before diffusion. The refractive indices are plotted in Fig. 11.

![Fig. 11. Extraordinary (left) and ordinary (right) refractive index distributions calculated using optiBPM.](image)

The substrate extraordinary refractive index was set to $n_e = 2.138615$ and $n_o = 2.211868$ for the ordinary both at 1531 nm. The diffused distributions show a maximum
index contrast of $\Delta n_e = 0.00857$ for the extraordinary index and $\Delta n_o = 0.00478$ for the ordinary.

(b) Optical modes profiles

Using the refractive index distributions shown in Fig. 11, the mode profiles for both TE and TM modes were calculated. The results are plotted in Fig. 12.

![Fig. 12. Calculated power density distributions for the TE and TM fundamental optical modes. (Left is TE; Right is TM.)](image)

In Fig. 13 are shown the calculated and measured horizontal profiles for the TE and TM modes. The calculated and measured vertical mode profiles for the TE and TM optical modes are plotted in Fig. 14.
For both optical modes at 1531nm, the horizontal profile fits to a Gaussian function while in the vertical fits to a Hermite-Gaussian function. For the optical TE mode at 1531nm, the measured horizontal size parameter is \(w_x(\text{TE}) = 8.7 \pm 0.9 \, \mu\text{m}\) and the vertical is \(d_y(\text{TE}) = 3.4 \pm 0.5 \, \mu\text{m}\). The calculated mode sizes in both directions were
similar to the experimental data within the uncertainties. A better match was found for the optical TM mode. The measured mode size parameters are \( w_s(TM) = 9.8 \pm 0.9 \, \mu\text{m} \) and \( d_s(TM) = 4.3 \pm 0.5 \, \mu\text{m} \).

The full-size of the optical input-fiber mode was also calculated and measured with a good agreement between them. The fiber mode size is \( s_s = 7.4 \pm 0.5 \, \mu\text{m} \). From the calculated optical fiber and waveguide modes, we can compute the mismatch-mode losses using the 3D overlap integral tool for each mode. The mismatch-mode losses are \( L_c(TE) = 0.5 \, \text{dB} \) and \( L_c(TM) = 0.7 \, \text{dB} \).

Similar deductions were carried out for the pump mode (1488nm). The horizontal size parameter of the optical mode is \( w_p = 7.5 \pm 0.9 \, \mu\text{m} \). In vertical direction is \( d_p = 3.8 \pm 0.5 \, \mu\text{m} \). The size of the optical fiber mode at 1488 nm is \( s_p = 6.5 \pm 0.5 \, \mu\text{m} \) leading to a mismatch-mode loss of \( L_c(\text{pump}) = 0.4 \pm 0.1 \, \text{dB} \).

After the simulation, inspect the intensity profile. There will be always showing high order modes. Only if their intensities decay to zero near the boundary, they truly exist. And the mode effective index must be high than the substrate refractive index. These are the criteria that help us to find when 2\textsuperscript{nd} mode comes out.

### 3.1.3. Coupling loss between Ti:LiNbO\textsubscript{3} modes and fiber modes

The Coupling loss between titanium diffused waveguide modes and fiber modes have been simulated. The titanium diffusion parameters have been swept.
(a) Simulation setup

The simulation was operated on OptiBPM. This simulation was trying to sweep two parameters: diffusion time and Ti thickness before diffusion and to find the best overlap between W/G and fiber modes (both TE and TM mode). The overlap represents the mode mismatch loss which is the major part of the coupling loss between the W/G and fiber. This part is very similar to part1. The difference is that we change the Er distribution to Fiber mode. The wavelength was set at 1531nm.

The fiber has the following parameters (Other parameters are set as default):

Core Radius: \( R_x = R_y = 4.07 \mu m \).

Refractive Index: Core=1.45204; Cladding=1.44681.

The single straight waveguide has the following parameters (Other parameters are set as default):

Strip Ti width before diffusion: 7\( \mu \)m.

Temperature coefficient: 303000 K;

Diffusion Temperature: 1025 \( ^\circ C \).

Diffusion Constants:

\[
D_{av} = 0.0199 \text{cm}^2 / s
\]

\[
D_{ad} = 0.0289 \text{cm}^2 / s
\]

(b) Results

The overlaps between W/G and fiber modes were calculated by Matlab.

\[
\text{coupling loss} = \frac{\int \psi_{fiber} \psi_{WG} dS}{\sqrt{\int \psi_{fiber}^2 dS \int \psi_{WG}^2 dS}}
\]  

(3.1)
Overlaps for TE modes in Table IV, the best mode is at Diffusion time=11 hrs, Ti thick=600Å.

<table>
<thead>
<tr>
<th>Diffus</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
<th>1500</th>
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<tbody>
<tr>
<td>4</td>
<td>0.733</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>0.598</td>
<td>0.806</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.511</td>
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<tr>
<td>7</td>
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<td>0.565</td>
<td>0.705</td>
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<td>0.624</td>
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<td>0.802</td>
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<td>0.707</td>
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<td>0.439</td>
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<td></td>
<td>0.527</td>
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</table>

Table IV. Overlap between waveguide and fiber mode for TE mode.

The x-axis is Titanium thickness before diffusion by angstrom, the y-axis is diffusion time by hour. The unit of data is dB.

Overlaps for TM modes in Table V, the best mode is at Diffusion time=15 hrs, Ti thick=1500Å.
Table V. Overlap between waveguide and fiber mode for TM mode.

<table>
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<tr>
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<td>-0.254</td>
<td>-0.255</td>
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<tr>
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<td>-0.257</td>
<td>-0.253</td>
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<td></td>
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</tr>
<tr>
<td>17</td>
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<td></td>
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</tr>
</tbody>
</table>

In this table, the x-axis is titanium thickness before diffusion (unit: angstrom), the y-axis is diffusion time by hour. The data is in unit of dB.

(c) Conclusions

(1). The best overlap for TE and TM mode are at different diffusion time and Ti Thickness.

(2). The average of the vertical and horizontal FWHM of the W/G mode is related to the overlap.

For the fiber, \( V_{FWHM} = H_{FWHM} = 5.56 \mu m \). For Ti waveguide, If

\[
\text{FWHM} = \frac{V_{FWHM} + H_{FWHM}}{2}
\]

is close to 5.56 \( \mu m \), then it will get best overlap. TM modes’
$FWHM$ are closer to 5.56 $\mu$m. So TM modes have better overlap. They are shown as Fig. 15.

Fig. 15. Mode size comparison between TE, TM and fiber.

3.2. Hybrid waveguides

3.2.1. Er doped Ti:LiNbO$_3$ waveguides

For the erbium doped waveguide simulation, best gain is our goal. There are two means in our consideration: increase the gain and decrease the loss. To increase the gain, we got to let the optical mode overlap better with the Er distribution. To decrease the loss, except lowering the propagation loss by better fabrication skills, we got to lower the coupling loss which is proportional to the overlap between waveguide mode and
fiber mode. We did these by sweep fabrication parameters: Ti diffusion time, Ti thickness before diffusion, As$_2$S$_3$ width and thickness, Er profile depth.

The softwares are OptiBPM, Optisystem and FIMMWAVE.

i. The simulation of Er gain versus Ti diffusion variation by OptiBPM.

The simulation was trying to sweep two parameters: diffusion time and Ti thickness before diffusion and to find the best overlap between W/G modeds (both TE and TM modes) and Er profile. The overlap represents the mode gain [47].

(1). Ti:LiNbO$_3$ mode solving.

Fig. 16. Ti:LiNbO$_3$ waveguide mode solving.
Ti:LiNbO₃ waveguide was simulated by OptiBPM. The mode (amplitude or intensity distribution) was shown in Fig. 16. The single straight waveguide has the following parameters (Other parameters are set as default): Strip Ti width before diffusion: 7μm; Temperature coefficient:303000 K; Diffusion Temperature: 1025°C; Diffusion Constants: $D_{ov} = 0.0199 cm^2 / s, D_{oh} = 0.0289 cm^2 / s$

(2). Er Distribution

![Image of Er density distribution](image)

Fig. 17. Er density distribution.

The Er density distribution $erfc(y)$ can be created by OptiBPM in Fig. 17 or by Matlab. We keep the diffusion depth at 6 μm to fit the experiment data.
(3). Calculate overlap between the waveguide mode and Er distribution.

Fig. 18. The calculation of overlap between mode and Er distribution.

The overlap between mode and Er distribution can be done by tools in OptiBPM (Fig. 18) or by Matlab code. The modes has been normalized to make sure \( \int E \cdot ds = 1 \). It keeps the total power=1. The Er distribution has been normalized to make Peak concentration on the surface equal to one: \( \text{Max}(I_{Er}) = 1 \).

And the overlap of gain can be expressed by, \( \text{Overlap} = \int E^2 \cdot I_{Er} \cdot ds \)

(a) Overlaps for TE modes (Table VI)
Table VI. Overlap versus Ti thickness and diffusion time for TE mode.

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<th>1400</th>
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</tr>
<tr>
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</table>

The x-axis is Titanium thickness before diffusion by angstrom, the y-axis is diffusion time by hour. The data is in unit of dB.

(b) Overlaps for TM modes (Table VII)
Table VII. Overlap versus Ti thickness and diffusion time for TM mode.

<table>
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<th>1000</th>
<th>1100</th>
<th>1200</th>
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</tr>
<tr>
<td>5</td>
<td>-4.698</td>
<td>-4.465</td>
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<tr>
<td>6</td>
<td>-4.814</td>
<td>-4.599</td>
<td>-4.42</td>
<td></td>
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<td>-4.736</td>
<td>-4.564</td>
<td>-4.418</td>
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</tr>
<tr>
<td>8</td>
<td>-5.064</td>
<td>-4.869</td>
<td>-4.706</td>
<td>-4.563</td>
<td>-4.441</td>
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<td>9</td>
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<td>-4.84</td>
<td>-4.701</td>
<td>-4.581</td>
<td>-4.474</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-4.968</td>
<td>-4.835</td>
<td>-4.716</td>
<td>-4.61</td>
<td>-4.514</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-4.957</td>
<td>-4.841</td>
<td>-4.735</td>
<td>-4.644</td>
<td>-4.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>12</td>
<td>-4.962</td>
<td>-4.858</td>
<td>-4.767</td>
<td>-4.68</td>
<td>-4.604</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>-4.974</td>
<td>-4.88</td>
<td>-4.797</td>
<td>-4.721</td>
<td>-4.651</td>
<td></td>
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<td></td>
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<tr>
<td>14</td>
<td>-4.991</td>
<td>-4.909</td>
<td>-4.833</td>
<td>-4.763</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>-5.016</td>
<td>-4.94</td>
<td>-4.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>16</td>
<td></td>
<td>-5.039</td>
<td>-4.972</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>-5.067</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The x-axis is Titanium thickness before diffusion by angstrom, the y-axis is diffusion time by hour. The data is in unit of dB.

(4). Conclusion.

The mode closest to the surface where has larger Er concentration has the best overlap: for TE, it is at 700Å, 5 hours; for TM, it is at 900Å, 7 hours.

ii. The simulation of Er gain versus Er intrinsic parameters’ variations by OptiSystemstem

In this part, we use Er doped waveguide module in Optisystem to simulate the gain. This module can calculate the gain from input waveguide cross-section refractive
index distribution and Er distribution. Pump and CW Laser parameters are in Table VIII and

Table IX. Er doped waveguide amplifier (EDWA) parameters are listed in APPENDIX B.

Table VIII. Pump laser parameters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1480</td>
<td>nm</td>
<td>Normal</td>
</tr>
<tr>
<td>Power</td>
<td>90</td>
<td>mW</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Table IX. CW laser parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1531</td>
<td>nm</td>
<td>Normal</td>
</tr>
<tr>
<td>Power</td>
<td>-30</td>
<td>dB</td>
<td>Normal</td>
</tr>
<tr>
<td>Linewidth</td>
<td>10</td>
<td>MHz</td>
<td>Normal</td>
</tr>
<tr>
<td>Initial phase</td>
<td>0</td>
<td>deg</td>
<td>Normal</td>
</tr>
</tbody>
</table>

(a) Gain vs. Er_Deff

In this part, we swept the Er_Deff (Er effective diffusion depth) from 3 μm to 7 μm to see how sensitive the gain changes with it. Fig. 19 and Table X is the Er ion density distribution setup and Table XI is the result.
Fig. 19. Optisystem setup: sweeping Er_Deff.

Table X. Er ion density setup

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er ion density distribution</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Er Profiles which have</td>
<td></td>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Deff=3~7 μm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table XI. Gain (dB) versus Er_Deff

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>6.1</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>-1.312</td>
<td>-1.262</td>
<td>-1.257</td>
<td>-1.286</td>
<td>-1.291</td>
<td>-1.336</td>
</tr>
<tr>
<td>TM</td>
<td>-1.095</td>
<td>-0.806</td>
<td>-0.545</td>
<td>-0.34</td>
<td>-0.323</td>
<td>-0.196</td>
</tr>
</tbody>
</table>
To Conclude, Fig. 20 shows that the gain is sensitive to $D_{\text{eff}}$ for TE modes, but not sensitive for TM modes. This may because that the TM modes are much deeper than TE mode.

(b) Gain vs. $Er_{\text{strip\_width}}$

We usually use planar Er (Fig. 21, but infinite wide) in simulation and in experiment. Now we try strip Er (Fig. 22) instead to see how sensitive the gain changes with the Er strip width.
Fig. 21. Planar diffused Er.

Fig. 22. Strip diffused Er.
Fig. 23. Optisystem setup: sweeping Er strip width.

Fig. 23 is the setting for Optisystem. Table XII and Fig. 24 are the results.

Table XII. Gain (dB) versus Er strip width.

<table>
<thead>
<tr>
<th>Er Width</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>-1.026</td>
<td>-1.031</td>
<td>-1.037</td>
<td>-1.045</td>
<td>-1.054</td>
<td>-1.064</td>
</tr>
<tr>
<td>TM</td>
<td>0.9096</td>
<td>0.9051</td>
<td>0.8989</td>
<td>0.891</td>
<td>0.8814</td>
<td>0.8701</td>
</tr>
</tbody>
</table>
To conclude, the gain is not sensitive to the strip width of Er.

(c) Gain vs. Pp vs. Cup

In this part, we simulated the gain change with pump power and up-conversion coefficient. The up-conversion coefficient represents how many percentage of power has been wasted on radiation to other wavelength.

Table XIII and Table XIV give the setup parameters.
Table XIII. Up_conversion parameters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculate upconversion effects</td>
<td>Yes</td>
<td>m^3/s</td>
<td>Normal</td>
</tr>
<tr>
<td>Cup</td>
<td>5~15e-24</td>
<td>m^3/s</td>
<td>Sweep</td>
</tr>
<tr>
<td>C3</td>
<td>100e-24</td>
<td>m^3/s</td>
<td>Normal</td>
</tr>
<tr>
<td>C14</td>
<td>70e-24</td>
<td>m^3/s</td>
<td>Normal</td>
</tr>
<tr>
<td>C16</td>
<td>70e-24</td>
<td>m^3/s</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Table XIV. Pump parameters setup

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1480</td>
<td>nm</td>
<td>Normal</td>
</tr>
<tr>
<td>Power</td>
<td>0~100(by 10)</td>
<td>mW</td>
<td>Sweep</td>
</tr>
</tbody>
</table>

Other parameters are the same as Table VIII and Table IX.

Fig. 25. Optisystem setup: sweeping C_{up}.
Fig. 25 is the setting for Optisystem. The results are in Fig. 26 and Fig. 27.

**Fig. 26.** Gain changes with $P_p$ and $C_{up}$ for TM mode.

**Fig. 27.** Gain changes with $P_p$ and $C_{up}$ for TE mode.
The conclusion is that the gain decreases with up conversion coefficient.

(d) Gain vs. ion density & life time

The setup is the same as Fig. 25 but with different parameters sweeping: ion density and Er metastable-lifetime.

Table XV shows the input parameters and Fig. 28 gives the results:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er metastable lifetime</td>
<td>1.7~2.7</td>
<td>ms</td>
<td>Sweep</td>
</tr>
</tbody>
</table>

Fig. 28. Gain changes with Er metastable lifetime.
Table XVI sweeps Er ion density and Fig. 29 gives the results.

### Table XVI. Setting for sweeping Er ion density.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er ion density</td>
<td>1E24–1.6E24</td>
<td>m⁻³</td>
<td>Sweep</td>
</tr>
</tbody>
</table>

![Gain vs Er Ion Density](image.png)

Fig. 29. Gain changes with Er ion density.

The conclusions are: (1) The gain increase with Er meta-stable Lifetime (Fig. 28); (2) The gain is proportional to the Er ion density (Fig. 29).

(e) Gain vs. Er thickness

Equation (2.35) and (2.36) show that the Er profile are proportional to the Er thickness \( \tau \) when diffusion time is fixed. And the Er ion density is also proportional to
the Er surface concentration. The optisystem simulation Fig1 showed that the Gain is proportional to the Er ion density. So it means the Gain is proportional to the Er thickness $\tau$. Overlap simulation

The overlap calculation is

$$\Gamma = \int E \cdot I_{Er} \, ds \quad (3.2)$$

$E$ is the normalized electric field and the $I_{Er}$ is the Er ion density profile which is also proportional to the Er thickness $\tau$. So the overlap simulation agree with that if the Er diffusion time doesn’t change, the Gain should be proportional to the Er thickness $\tau$. Measured data in Table XVII are from experiments, and the best results (>1dB) were chosen.

### Table XVII. Propagation gain versus Er thickness

<table>
<thead>
<tr>
<th>Er Thickness (nm)</th>
<th>Propagation Gain (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TE</td>
</tr>
<tr>
<td>11</td>
<td>0.1</td>
</tr>
<tr>
<td>11</td>
<td>-0.6</td>
</tr>
<tr>
<td>11</td>
<td>-0.1</td>
</tr>
<tr>
<td>14</td>
<td>0.3</td>
</tr>
<tr>
<td>17</td>
<td>0.9</td>
</tr>
<tr>
<td>19</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Fig. 30. Gain (dB/cm) changes with Er thickness for TE mode.

Fig. 31. Gain (dB/cm) changes with Er thickness for TM mode.
The Fig. 30 and Fig. 31 agree with (3.2). If we increase the Er thickness while keeping the depletion time shorter than the diffusion time, we can get more gain.

### 3.2.2. As$_2$S$_3$ waveguides on top of the TiLLiNbO$_3$ waveguides

In the part, we want to introduce As$_2$S$_3$ ridge waveguide on top of Ti diffused LiNbO$_3$ waveguide to pull the mode to surface to increase the gain. We used FIMMWAVE, by Photon Design Ltd, which is capable for solving these kind of mixed waveguides including both diffused and ridge guide to solve the optical modes by film mode matching (FMM) method at 1531 nm for the signal and 1480 nm for the pump. Fig. 32 shows the structure of the vertical integration between an Er:Ti:LiNbO$_3$ and an As$_2$S$_3$ waveguides. The device is made on an x-cut y-propagation lithium niobate substrate with planner diffused Er. The titanium diffused waveguide is in the center, while the As$_2$S$_3$ waveguide is placed next to it above the surface.

![Fig. 32. Schematic picture of our structure.](image-url)
Fig. 33. Refractive index profile for TM mode: Z-axis is refractive index (1.0-2.4); X-axis is waveguide width (0-40 μm); Y-axis is waveguide depth (0-25 μm).

Fig. 33 illustrates the refractive index profile of the waveguide. The index value is shown in z-axis and the waveguide cross section is shown in x-y plane. Corresponding to the structure in Fig. 33, the As₂S₃ waveguide is represented by the protruding pole (n=2.4) with the bump next to it, on which the swelled part is the titanium diffused region in lithium niobate substrate (the bulk part, nₜₐₚₙ=2.21+Δnₜ₁-diffused-TM, nₜₑ=2.13+Δnₜ₁-diffused-TE). The air cladding (n=1) is at the bottom.

As we swept the dimensions of the As₂S₃ waveguide, we found that the thickness of the As₂S₃ thin film is the most sensitive parameter. The As₂S₃ width must be larger than 2 μm to pull up the mode, but further increasing the width to infinity only changes the overlap by 17%. However, changing the thickness from 0 to 0.5 μm changes the overlap by 230%. So, we set the As₂S₃ width to 4 μm and subsequently swept the thickness.
Fig. 34. Confinement factor in As$_2$S$_3$ at signal wavelength (1531 nm) for both TM and TE modes.

The resulting confinement factor which is the percentage of optical intensity in As$_2$S$_3$ is shown in Fig. 34. It increases with the As$_2$S$_3$ waveguide thickness.

Fig. 35. (1) Top left is the TM mode without As$_2$S$_3$. (2) Top right is the TM mode with 0.28 μm thick As$_2$S$_3$. (3) Bottom left is the TE mode without As$_2$S$_3$. (4) Bottom right is the TE mode with 0.2 μm thick As$_2$S$_3$. 
The Er profile was measured by Secondary Ion Mass Spectrometry (SIMS). The effective depth is $d_{eff} = 4.9 \mu m$ after fitting for the complementary error function. Using the optical modes and Er profile, the overlap integral $\Gamma$ between the modes and Er profile expressed by (6) can be simulated. Fig. 35 shows the simulated mode profiles and the mode pulling effect. Having considered the overlap between the mode and Er (Fig. 36), and pump effects (Fig. 37~Fig. 41), the optimum thicknesses for TM and TE are found to be 280 nm and 200 nm respectively.

Fig. 36 shows the overlap of the signal modes and Er profile. We normalized all the overlap data relative to the overlap when the As$_2$S$_3$ thickness equals to zero. For TM mode, the overlap starts from 1 and increases slowly at 0-0.2 $\mu m$, but changes dramatically at 0.25-0.3 $\mu m$. After 0.3 $\mu m$, it falls. After 0.5 $\mu m$, it falls below 1 since 45% power of mode has spread into the As$_2$S$_3$ area and can’t be pumped since there is no Er there. The mode is over-pulled. The overlap for the TE mode shows a similar curve, with the peak at 0.21 $\mu m$.

The As$_2$S$_3$ waveguide not only enhances the modes and Er overlap, but also influences the pump to signal mode mismatch $O_{S&P}$ and pump to fiber modes coupling $O_{P&F}$. They are defined in (3.3) and (3.4) and plotted as curves in Fig. 36.

$$O_{S&P} = \int_{A} \Phi_s(x, y) \Phi_p(x, y) dx dy$$ \hspace{1cm} (3.3)

$$O_{P&F} = \int_{A} \Phi_p(x, y) \Phi_f(x, y) dx dy$$ \hspace{1cm} (3.4)
\( \psi_s, \psi_p, \psi_f \) are the signal, pump and fiber modes. The fiber mode has a mode field diameter (MFD) of 9.9 \( \mu \)m at 1480 nm, measured by the beam profiler.

Fig. 36. Overlap data: Signal modes and Er overlap.

Fig. 37. Pump effects for TM mode: (1) Pump and signal mode overlap; (2) Pump and fiber modes overlap.
Fig. 38. Propagation gain versus pump power for Er:Ti:LiNbO$_3$ waveguide without As$_2$S$_3$ for TM mode.

Sample fabrication parameters are discussed in Chapter IV and the measurement setup is discussed in Chapter V.

Fig. 39. Effective gain influenced by pump effects for TM mode.
These pump-related overlaps change the amount of pump power interacting with Er ions and the signal mode. They impact pump efficiency, and thus are similar to changing the input pump power. We multiply these two overlap values and take the product as the pump efficiency ratio. Experimentally, we measured the gain versus pump power, shown in Fig. 38, for the waveguide without As$_2$S$_3$. Therefore, the effective gain in Fig. 39 is computed from the gain versus pump power curve in Fig. 38 while the effective pump power is calculated by multiplying the pump efficiency ratio and pump power (144mW).
Based on (7), this gain should be proportional to the signal mode and Er overlap. As shown in Fig. 40, the final simulated propagation gain versus As$_2$S$_3$ thickness is obtained as the product of the curves in Fig. 36 and Fig. 39. From Fig. 37, the optimum thickness for gain is found to be 0.28 μm, which is a -0.2 μm shift from Fig. 36 due to pump effects. Our experimental data for several As$_2$S$_3$ thicknesses is also plotted, and it matches well with the simulated curve. The same process can be performed for TE polarization and the final simulated gain is plotted in Fig. 41. The optimum thickness is 0.20 μm, which is a -0.1 μm shift from Fig. 36 due to pump effects.

Coupling losses between the mode and the fiber must be considered since the mode shape is changed. The coupling losses include Fresnel reflections, which are constant, and the mode shape mismatch, which is the overlap between the waveguide mode and fiber mode. The coupling losses of the Ti:Er:LiNbO$_3$ waveguide have been measured at 1531nm for TM mode (0.5dB) and TE mode (0.9dB).
The waveguide modes for varying As$_2$S$_3$ thicknesses have been simulated at 1531 nm for both TM and TE polarizations. The fiber mode with Gaussian distribution has a mode field diameter (MFD) of 10.2 μm at 1531 nm, measured by the beam profiler. The relative horizontal and vertical shifts between waveguide and fiber modes were scanned to achieve the best alignment. Fig. 42 shows the calculated coupling overlap data, which is normalized by the overlap without an As$_2$S$_3$ waveguide. The coupling overlap for an As$_2$S$_3$ thickness of 280 nm with TM polarization is 1.14 (+0.57 dB), normalized to the overlap with no As$_2$S$_3$, even better than the overlap without As$_2$S$_3$. This is because the TM mode for the 7 μm wide Ti:LiNbO$_3$ waveguide is larger than fiber mode, but the As$_2$S$_3$ waveguide reduces the mode size and better matches the fiber mode, reducing coupling loses.

For TE polarization at 200 nm, the normalized coupling overlap is 0.946 (-0.24 dB). It can be overcome by introducing a tapered As$_2$S$_3$ waveguide [48]. The waveguide width can increase/decrease gradually from 0.5 μm to 4 μm in 3 mm length at the input/output ports of the waveguide. So the mode profile at the waveguide ends is the same as the normal Ti:LiNbO$_3$ waveguide mode while in the center it is the pulled-up by the As$_2$S$_3$ waveguide.
3.3. Electro-optical devices

3.3.1. As$_2$S$_3$ waveguide assisted EO phase shifter

In this section, the optimum As$_2$S$_3$ overlay with varying width and height to produce the smallest required EO tuning voltage has been explored.

The EO solver in FIMMWAVE can solve the situation when the electrical field is perpendicular to the waveguide. The device is the phase shifter. The As$_2$S$_3$ waveguide is side coupled to the Ti waveguide, and thickness and width have been swept.

To determine the sweet spot of EO effect under various values of the As$_2$S$_3$ width, thickness and electrode gaps, EO effect simulations are required. To test the EO effect on the sample, the waveguide must be designed to a MZI pattern as shown in Fig. 43, the top and bottom arm are identical for titanium waveguide and electrodes. The top arm has an extra As$_2$S$_3$.
Fig. 43. MZI pattern with 1μm gap between Ti (or As$_2$S$_3$) and electrodes (The gap is the distance between Ti (or As$_2$S$_3$) and electrodes).

Fig. 44. EO effect simulation for TM modes. (Electrodes gap=17 μm, As$_2$S$_3$ width are swept from 2.5~4.5 μm).
From Fig. 44, the best thickness for EO enhance is at 0.42 \( \mu \text{m} \) for TM modes, independent of As\( _2 \)S\( _3 \) width. Also, for TE modes from Fig. 45, it is at 0.26 \( \mu \text{m} \).

Simulations to find best electrodes position have been performed.

**TM Modes:** As\( _2 \)S\( _3 \) thickness is 0.42\( \mu \text{m} \) (from Fig. 44), width is 0–5\( \mu \text{m} \). V=25V.

Electrodes are attached to the edge of As\( _2 \)S\( _3 \) (top) and Ti (bottom) when Gap=0 \( \mu \text{m} \). The gap is the distance between As\( _2 \)S\( _3 \) and electrodes. The results are in Table XVIII.
Table XVIII. EO effects for TM modes: Varying As$_2$S$_3$ width and electrodes gap

<table>
<thead>
<tr>
<th>(e$^{-2}$)</th>
<th>As$_2$S$_3$ width (um)</th>
<th>0</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaps=0um</td>
<td>With As$_2$S$_3$</td>
<td>3.77095</td>
<td>3.88716</td>
<td>4.10165</td>
<td>5.34425</td>
<td>6.13155</td>
<td>6.04078</td>
<td>5.80826</td>
<td>5.59965</td>
<td>5.3224</td>
<td>5.10276</td>
</tr>
<tr>
<td>Gaps=0.5um</td>
<td>With As$_2$S$_3$</td>
<td>3.70088</td>
<td>3.72848</td>
<td>3.89317</td>
<td>4.7914</td>
<td>5.24321</td>
<td>5.12513</td>
<td>4.93693</td>
<td>4.74837</td>
<td>4.5715</td>
<td>4.40668</td>
</tr>
</tbody>
</table>

TE Modes: As$_2$S$_3$ thickness is 0.26µm (from Fig. 45), width is 0~5µm. 25V.

Table XIX. EO effects for TE modes: Varying As$_2$S$_3$ width and electrodes gap.

<table>
<thead>
<tr>
<th>(e$^{-2}$)</th>
<th>As$_2$S$_3$ width (um)</th>
<th>0</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
</tr>
</thead>
</table>
The TE simulation results are in Table XIX. From Table XVIII and Table XIX, the best As$_2$S$_3$ widths can be found at 2.5 $\mu$m for both TE and TM modes. So the best dimensions are 2.5 $\mu$m wide and 0.42 $\mu$m thick for TM mode and 2.5$\mu$m wide and 0.26$\mu$m thick for TE mode.

EO effect is proportional to the overlap of optical mode in LN and the e-field. (It is calculated in x and y direction separately in FIMM WAVE and summed up later.) So if the peak of the mode overlaps with the peak of the e-field (Fig. 46 and Fig. 47), then it is suppose to get good EO effect. As$_2$S$_3$ pulls the mode up, so if the e-field is higher there, it will increase the EO effect. But over-pulling will make the mode out of LN region and get EO effect down. Increase the width has two effects: (1) Pull the mode towards As$_2$S$_3$. (2) As$_2$S$_3$ gets wider and the mode gets closer to the electrodes. Increase the thickness has only one effect: pulling the mode toward As$_2$S$_3$. 
Fig. 46. Potential of the asymmetrical electrodes.

Fig. 47. Potential of the symmetrical electrodes.
3.3.2. Nano-slot EO phase shifter

Nano slot is a novel structure which brings large EO effect [49]. Simulation setup by FIMMWAVE is shown as Fig. 48. The two rectangular Si waveguides are 100nm wide and 480nm high. The slot is 15nm wide. The bottom substrate is x-cut LiNbO$_3$ and the top cladding is air.

The benefit of this structure is to use Si waveguide to confine the light inside but let LN below (when slot is filled with air) or in between (when the slot is filled with LiNbO$_3$). Since the Si is doped so it can be electrode too. Then the electrical field and optical field can be overlapped pretty well. And due to the high refractive index of Si is very high, the optical field is well confined in this small area and the optical density is very high. All of these benefits will lead to a high electro-optical effect.

Complex FMM solver is required for this job since the Si waveguide is both optical and electrical lossy. $\lambda$ is at 1550nm.
After the optical mode solving, use EO solver and apply voltage on the two Si electrodes to get the electrical field distribution. The simulated results are shown in Fig. 49 for 2D electrical field and in Fig. 50 for 3D electrical field.
Fig. 49. 2D $E_x$ field of nano slot from complex solver (TE mode).

Fig. 50. 3D $E_x$ field of nano-slot from the complex solver (TE mode).
The equations calculate the EO effect in (3.5) and (3.6) [49].

\[
\Gamma = \frac{d}{V} \int \int_{s} E_{opt}^{2} E_{x}^{2} \, dx \, dy
\]

(3.5)

where \(d\) is the width of the slot, \(V\) is the voltage. \(E_{opt}\) is the optical field, \(E_{x}\) is the electrical field (in this situation, \(E\) field is \(x\)-component).

\[
V_{\pi} L = \frac{\lambda}{n r_{33}} \frac{d}{\Gamma}
\]

(3.6)

After the mode and electrical field solving, load these two profiles into matlab and do the calculation in (3.5) which is the equation calculates the overlap of the electrical field and the optical field. It is similar to overlap between Mode and Er profile. \(V_{\pi}\) then can be calculated in (3.6).

Window size also needs to be appropriate. When window size: 4 \(\mu m\)*7 \(\mu m\), resolution 500*500, the results are shown in Table XX.

<table>
<thead>
<tr>
<th></th>
<th>FIMMWWAVE</th>
<th>RSOFT [49]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Gamma)</td>
<td>0.0848</td>
<td>0.062</td>
</tr>
<tr>
<td>(V_{\pi} L) (V.cm)</td>
<td>0.60</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Then shrink window size to 2 \(\mu m\)*3 \(\mu m\), resolution 500*500. The slot area is 100nm*480nm (25*120 points). Relative error=2/25=8%.

(1).Nano slot filled with air:
Table XXI. EO results when window size= 2 μm*3 μm, slot filled with air.

<table>
<thead>
<tr>
<th></th>
<th>FIMMwave</th>
<th>RSOFT [49]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Γ</td>
<td>0.0624</td>
<td>0.062</td>
</tr>
<tr>
<td>$V_L$</td>
<td>0.8147</td>
<td>0.82</td>
</tr>
</tbody>
</table>

(2). Slot filled with LN:

Table XXII. EO results when window size= 2 μm*3 μm, slot filled with LiNbO₃.

<table>
<thead>
<tr>
<th></th>
<th>FIMMwave</th>
<th>RSOFT [49]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Γ</td>
<td>0.3251</td>
<td>0.252</td>
</tr>
<tr>
<td>$V_L$</td>
<td>0.1564</td>
<td>0.2</td>
</tr>
</tbody>
</table>

After shrinking window size and using complex solver, the simulated results by FIMMwave are very close to the data in [49] in Table XXI and Table XXII. Since these simulation results are repeatable, we can use this method to simulate other structures and consider the loss in the same time to optimize the modulator design.

3.4. Multilayer and Bragg reflectors

3.4.1. Multilayer reflectors

The high, low and substrate index are 2.4, 1.45 and 2.1 respectively for As₂S₃, SiO₂ and LiNbO₃ (n₀). The simulations are based on the multilayer equations in Chapter II.

(a) Reflectance change with high & low index pairs
Fig. 51 shows the intensity reflectance and phase reflectance at center wavelength change with the number of high, low index pairs.

![Intensity and phase reflectance graph](image)

Fig. 51. Intensity and phase reflectance at center wavelength (1531nm).

(b) Reflectance change with wavelength

The Fig. 52 and Fig. 53 showed the reflectance change with wavelength. Refractive Indices are constants with wavelength change.
Fig. 52. Reflectance when number of the high & low pairs N=1,2,3.

Fig. 53. Reflectance when number of the high & low pairs N=7.
3.4.2. Bragg grating reflectors

We want to simulate the reflection spectrum of the Bragg gratings and design it to fulfill our requirements for partial reflector: reflection peak at 1531nm at reflection zone width about 10nm. The reflectivity can be adjusted by changing the length of the grating.

(a) Si overlay simulation

Bragg gratings in Fig. 54 have been achieved by Si etch on Ti:LiNbO₃ [50].

![Fig. 54. Schematic illustration of the waveguide with Bragg gratings.](image)

The parameters are listed in Table XXIII and the reflection spectrum is shown in Fig. 55.

<table>
<thead>
<tr>
<th>film</th>
<th>Λ</th>
<th>Thickness*</th>
<th>length</th>
<th>Etch gas</th>
<th>Wavelength</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-a</td>
<td>350nm</td>
<td>10/105nm</td>
<td>2 mm</td>
<td>C4F8/O2</td>
<td>1542.7</td>
<td>0.05nm</td>
</tr>
</tbody>
</table>

Table XXIII. Parameters of Bragg grating (TE polarization, *thickness: etched).
Fig. 55. Broadband transmittance spectrum for TE input polarization [50].

The simulation was performed by FIMMProp, and the simulation setting is shown below. The substrate is 7 μm wide Ti:LiNbO₃ with 95nm titanium diffused by 9hours. The number of high/low pairs (periods) is N=10⁶.

The high refractive index sections have 1nm Si overlay on top. The simulated effective index n₁=2.140993166, length L₁=1.531/4/n₁. The low refractive index sections have no Si overlay on top. The simulated effective index n₂=2.140991681, length L₂=1.531/4/n₂;
The simulated transmission and reflection spectrum is shown in Fig. 56. The center wavelength is exactly at 1531 nm. We can see that even the number of the periods reaches up to $10^6$, the reflection was still very low <0.3.

(b) As$_2$S$_3$ waveguide simulation

First design (in Fig. 57) is two-section design.

The simulation setup and result are listed below. The substrate is x-cut LN, no Ti diffused WG for faster simulation. TM modes were simulated. The high refractive index sections of As$_2$S$_3$ WG have thickness 0.47 μm, width 3.5 μm, index $n_1$=2.22806000; Low refractive index sections have As$_2$S$_3$ WG thickness 0.47 μm, width 2.7 μm, index $n_2$=2.223421981. Both high and low index sections keep single mode. The average index $(n_1+n_2)/2$=2.2257409905. The lengths of every section are calculated as taking
The average of the high and low refractive index: \( L_1 = L_2 = 1.531/4/[(n_1+n_2)/2] = 0.1720 \ \mu\text{m} \).

The \( L_{\text{period}} = L_1 + L_2 = 0.3439 \ \mu\text{m} \). The number of periods \( N = 5000 \) and the length of grating = 1.72 mm.

Fig. 57. Taper teeth structure FimmProp simulation setup.

Since the reflection depends on the refractive index difference, we have to make width difference big enough: \( 3.5 - 2.7 = 0.8 \ \mu\text{m} \). Fig. 58 shows the reflection and transmission spectrum. It fulfilled our requirements.
In the first design, although it can work on simulation, but the “tooth tips” are too sharp for the real fabrication. Then the second design which is the four-section design which changes the teeth of the grating from the triangular shape into the trapezium shape. The real fabrication is based on this design and the etched As$_2$S$_3$ patterns are shown in Chapter V.

Second design is shown in Fig. 59, Fig. 60, Fig. 61 and the parameters are listed below.
For As$_2$S$_3$ on Ti:LiNbO$_3$ structure, $w_l$=wavelength=1.531nm, $w_{i1}$=3.5 µm; $w_{i2}$=2.7 µm. The simulated refractive index data is listed: $n_1$=2.232942088, $n_2$=2.231268554, $n_3$=$(n_1+n_2)/2$=2.232105321, $n_4$=$(n_1+n_2)/2$=2.232105321. The lengths for every section are calculated:

$L_1=\frac{w_l}{8}/n_3=0.085737441777282$ µm ;
$L_2=\frac{w_l}{8}/n_2=0.085769594904621$ µm;
$L_3=\frac{w_l}{8}/n_3=0.085737441777282$ µm;
$L_4=\frac{w_l}{8}/n_1=0.085705312747905$ µm;

The length of one period is $L_0=L_1+L_2+L_3+L_4=0.342949791207091$ µm. The full length for the gating area is $L_{\text{full}}=L_0*5000=1714.748956035456$ µm. The taper length is $L_{\text{taper}}=500$ µm. The taper tip length $L_{\text{end}}=1$ (required in FIMM Prop). The
whole length of this structure is \( L = L_{end} \times 2 + L_{taper} \times 2 + L_0 \times 5000 = 2716.748956035456 \) µm.

Fig. 60. Whole length of the four-section design of Bragg grating.

Fig. 61. Generated GDS file of the Bragg grating. (Taper + teeth).
CHAPTER IV

FABRICATION AND PROCESS DEVELOPMENT*

4.1. As$_2$S$_3$ waveguide assisted Er: Ti: LiNbO$_3$

A 13 nm-thick Er layer was sputtered onto a 3cm long x-cut, y-propagating LiNbO$_3$ substrate and diffused at 1100°C for 120 hours. The resulting Er profile measured by Secondary Ion Mass Spectrometry (SIMS) is shown in Fig. 62. Then, a 95 nm titanium film was sputtered, patterned, and diffused for 9.5 hr in wet breathing air ambient. The end facets of the waveguide chip were then polished to optical quality, and the Er:Ti:LiNbO$_3$ waveguide tested by butt-coupling single-mode fibers. The mode profiles were shown in Fig. 35. The mode field diameter (MFD) is defined as the full width at 1/e$^2$ for mode intensity profile. They are measured for TM mode (vertical: 10.7 μm, horizontal: 13.9 μm) and TE mode (vertical: 5.6 μm, horizontal: 8.6 μm). After that, a thin film of As$_2$S$_3$ (refractive index: 2.4) was deposited using RF magnetron sputtering at varying thicknesses (0 nm, 280 nm, 300 nm and 375 nm) with a constant 4 μm width. The top view in Fig. 63 shows that the As$_2$S$_3$ waveguide is placed next to the bump of the titanium diffused waveguide, so as to keep the As$_2$S$_3$ waveguide away from the rough surface of the bump.

* Part of this chapter is reprinted with permission from "Gain improvement of Er-Ti:LiNbO3 waveguide amplifier by an As2S3 overlay waveguide" by Xiaomin Song, Wee Chong Tan, William Timothy Snider, Xin Xia, and Christi K. Madsen, IEEE Photon. J., 3, 686-695, 2011, copyright 2011 by IEEE.
4.2. As$_2$S$_3$ ring on Er: Ti: LiNbO$_3$

4.2.1. Image reversal

The recipe in Fig. 64 and Table XXIV was tested for best performance.
Table XXIV. Image reversal recipe.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Spin</th>
<th>Soft Bake</th>
<th>Expose</th>
<th>Reverse Bake</th>
<th>Flood</th>
<th>Develop</th>
<th>Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC 496 trial2, pic3</td>
<td>40s@4000RPM</td>
<td>1min@85C</td>
<td><a href="mailto:15s@4.1mW">15s@4.1mW</a>/cm²</td>
<td>1min@105C</td>
<td><a href="mailto:65s@4.1mW">65s@4.1mW</a>/cm²</td>
<td>25s (6.5 MF312)</td>
<td>D8</td>
</tr>
</tbody>
</table>

4.2.2. Lift-off

After image reversal or negative patterning, here comes the lift-off process.

It is 3 min in acetone then put the beaker into ultrasonic until Er layer totally lifted off (about 2-3min).
During the ultrasonic lift-off process, I used two sharp-end tweezers to hold the samples (Fig. 65). This made the samples face down and avoid the re-deposition of the Erbium (or other film) pieces.

Fig. 65. Samples were set face down during the lift-off.

4.3. Er doped Ti: LiNbO$_3$ cavity

4.3.1. Multilayer deposition

Multilayer films have been deposited on the polished sides of the LiNbO$_3$ samples. As$_2$S$_3$ and SiO$_2$ stacks are shown in Fig. 66. It has three As$_2$S$_3$ and two SiO$_2$ layers. The intensity reflectivity is 0.8233 theoretically.
Table XXV. Multilayer index and thicknesses.

<table>
<thead>
<tr>
<th></th>
<th>As$_2$S$_3$</th>
<th>SiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda=1531$nm</td>
<td>2.438</td>
<td>1.444</td>
</tr>
<tr>
<td>Refractive Index: n</td>
<td>156.99</td>
<td>265.06</td>
</tr>
</tbody>
</table>

The thicknesses for every layer have been calculated: $thickness = \frac{\lambda}{4n}$ in Table XXV. The films are deposited on the right edges of the samples as Fig. 67 shows.
4.3.2. E-beam lithography for Bragg grating

UT Austin E-beam lithography training; Process:

a) Loading wafers (+pumping).
b) Transfer of wafers;
c) Calibration and exposure;

The sample loading was done in room 1 (Fig. 68). Then transferring wafers and exposure were done in room 2 (Fig. 69). The sample loading should be very careful or the load lock could be damaged (Fig. 70). Transferring wafer should be done when the lights in Fig. 71 are all green. Then the calibration and exposure could be done by following the lab manuals.
Fig. 68. E-gun chamber in room 1 (with load lock)
Fig. 69. Main console in room 2.

Fig. 70. Cassette holder lock.
The whole processes of making As$_2$S$_3$ Bragg gratings include: E-beam lithography, RIE etch, O2 ashing, HF.

Recipes:

(a) E-beam lithography

(1) **Positive** Resist: **ZEP 520A**

**Spin parameter:** 500rpm 5sec 100rpm ramp; 6000rpm 35sec 1000 ramp.

(P.R thickness 350nm)

**Soft (pre) bake:** 150 °C hotplate 2.5min (was 180 °C, too high for As$_2$S$_3$)

**Exposure time:** about 20 sec for area 3.5×344 μm$^2$.

Develop: Amyl Acetate Developer, 1’30” develop, 1’ rinse in IPA.

(2) Negative resist: NEB 31A3

Spin parameter: 500rpm 5sec 100rpm ramp; 3000rpm 60sec 1000 ramp.

Soft (pre) bake: 110 °C hotplate 2min.

Exposure time: about 3 sec for area 3.5×344 μm².

Dose (Unit: uC/cm²): 14, 13, 12, 11, 10

Reverse bake: 95 °C hotplate 45sec (critical).

Develop: AZ 300 MIF, 30 sec.

(Photo resist remover: Remover PG: N. Methylypyrrolidinone (NMP). It can be replaced by RIE O₂ ashing.)

(b) RIE

Same recipe as Ti/ As₂S₃ etching.

RC620, NEB: 3’30”+30” +30” +30”. Stop until yellow color gone (Fig. 72).

RC607, ZEP: 4’30”. Photo-resist gone, surface looks like titanium film (Fig. 73).
Fig. 72. RC620, NEB 3’30” in the etching process.

Fig. 73. RC607, ZEP: after 4’30” RIE etching.
(c) O₂ ashing

It is the same recipe as As₂S₃ O₂ ashing.

RC 607, ZEP: 2’20”. No change (Photo resist was gone already)

RC620, NEB: 2’20”+8’20”+30”, until the surface of the As₂S₃ strip looks smooth.

(d) HF

RC607 and RC620: 1min in diluted HF (HF:H₂O =1:20).

Then the samples are ready for optical testing or SEM imaging. The SEM pictures of Bragg gratings are shown in Chapter V.

After E-beam lithography recipe discussion, the E-beam pattern design for cavities can be performed. Top and left boundaries need rough polishing (1st pad) before photolithography to get better control of the positions of the align marks. Also it may require marks for the positions of the tapes.

E-beam advantage: “Self alignment”, using one-time patterning to make W align-mark (Fig. 74) and Ti (Or P.E.) waveguides (WGs) which needs Teflon tape to do selective deposition (Fig. 75).

E-beam As₂S₃ ring can be designed for both TE and TM modes, tip width can be narrower (~0.5 μm) for TE mode. Proton exchange and Ti patterns are both designed.

Calibration for the Tungsten etch rate and comparison to the Ti and SiO₂ etch rate: W etch, 3’30” for 1500 Å; Ti etch: 4’ for 950Å. Tungsten area can be over etched because it doesn’t need high quality waveguide. So the final W thickness is about 2000Å along with 950Å titanium.
Fig. 74. Design diagram of $\text{As}_2\text{S}_3$ grating by E-beam lithography.

Fig. 75. Selective deposited sample. Top and bottom areas are tungsten, central area is titanium.
CHAPTER V
MEASUREMENT AND RESULTS*

5.1. As$_2$S$_3$ waveguide assisted Er: Ti: LiNbO$_3$

A schematic of the measurement setup for the optical gain is detailed in Fig. 76. We use the LUNA optical vector analyzer (OVA) which has a built-in wavelength swept source (left port) and detector (right port). It can scan the loss (or gain) of the device under test (DUT) over a wavelength range 1520-1608 nm for both TM and TE polarizations.

Fig. 76. Schematic of the propagation gain measurement.

* Part of this chapter is reprinted with permission from "Gain improvement of Er-Ti:LiNbO3 waveguide amplifier by an As2S3 overlay waveguide" by Xiaomin Song, Wee Chong Tan, William Timothy Snider, Xin Xia, and Christi K. Madsen, IEEE Photon. J., 3, 686-695, 2011, copyright 2011 by IEEE.
The forward pump laser power is 59mW and the backward pump laser power is 85mW before being launched into the waveguide and the pump wavelength is 1480 nm. The backward pump was TM polarized to increase the overlap with the signal mode. Signal and pump are combined by two WDM couplers. Two power meters are used to separately optimize fiber-to-device alignment and pump polarization.

There is only a small difference for measured insertion losses with the pump on and off for wavelengths longer than 1590 nm. Thus, the pump has little effect for this wavelength range, and we use the average value for the pump on and off conditions as the absolute reference for the propagation gain calculation. Note, our Ti:LiNbO$_3$ waveguide loss has negligible wavelength dependence (≈0.1 dB variation over 1520-1605 nm). The propagation gain is extracted directly from the spectral data of the waveguide itself, avoiding uncertainties in estimating the fiber-to-waveguide coupling loss in the gain calculation.

First, we measured the Er:Ti:LiNbO$_3$ waveguide without an As$_2$S$_3$ layer. Then, we fabricated an As$_2$S$_3$ waveguide on top. The best gain was found with an As$_2$S$_3$ thickness of 280 nm (see Fig. 40). The propagation gain was enhanced by 0.9 dB/cm from 1.1 to 2 dB/cm (see Fig. 77). The peak amplification wavelength is at 1531 nm. Compared to the case without the As$_2$S$_3$ waveguide, the propagation gain in the Er:Ti:LiNbO$_3$ waveguide with the As$_2$S$_3$ waveguide has been improved substantially for the same launched pump power conditions, as predicted by simulation. Taking into account propagation loss (0.4dB/cm for TM mode) and coupling losses, the net gain for this 3cm long sample has been improved from 1.1dB to 3.5dB.
Our approach provides the opportunity for enhanced device functionality. As one example, the As$_2$S$_3$ channel waveguides can become part of a vertically-integrated ring resonator, enabling the signal to be amplified and potentially compensate the ring’s roundtrip loss. Thus, ideal all pass filters may be realized in the future as well as hi-Q, gain-tuned rings.

5.2. As$_2$S$_3$ ring on Er: Ti: LiNbO$_3$

We did our first test sample to see if the gain in the feedback loop can compensate the roundtrip loss. The mask design is shown in Fig. 78. The blue straight line is Ti:LiNbO$_3$; the pink racetrack is As$_2$S$_3$ ring and the green area is the Er doped region. We used selective doped Er because we don’t want to induce excess loss in the ring where has no pump power since un-pumped Erbium ion can absorb signal power.
Fig. 78. Erbium area, As$_2$S$_3$ ring and titanium WG on the mask design.

Table XXVI. Er ring parameters.

<table>
<thead>
<tr>
<th>Ring Parameters</th>
<th>Ring length</th>
<th>Ring Radius</th>
<th>Ring Round Trip</th>
<th>Measured FSR</th>
<th>FSR 3.4815</th>
<th>Er region length</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC436</td>
<td>12mm</td>
<td>0.4mm</td>
<td>26.5mm</td>
<td>0.03651nm</td>
<td>4.77 GHz</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>WG9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 79. Picture of Er and Ti diffused areas.

Fabrication processes are the same as 5.1 except the Er patterning. The Er area is opened by image reversal. Then deposit 13nm Er on the sample. After deposition, lift-off was performed to remove Er in other area (Fig. 79). The Er doped area has 60nm height bump.
The detailed parameters are listed in Table XXVI. The test setup is the same as chapter 5.1. We test the sample before and after the fabrication of the As$_2$S$_3$ ring.

Fig. 80. Gain measurement without As$_2$S$_3$ ring.

Left: Pump on; Right: Pump off.

In Fig. 80, the left picture shows the gain curve when pump is on, the right one shows the absorption curve when pump is off. They are measured before As$_2$S$_3$ ring fabrication.

In Fig. 81, the left picture shows the gain curve when pump is on, the right one shows the absorption curve when pump is off. They are measured after As$_2$S$_3$ ring fabrication. Compare Fig. 80 and Fig. 81, the TE modes doesn’t change much because it can’t be coupled into the ring. But the TM modes changed a lot because they can couple into the ring and show the ring response.
Fig. 81. Gain measurement with As$_2$S$_3$ ring.

Left: Pump on; Right: Pump off.

The zoom-in ring response is in Fig. 82. Fitted with ideal ring function, we can get the round trip loss and coupling ratio.
Table XXVII. RC 436 fitted round trip loss and coupling ratio.

<table>
<thead>
<tr>
<th>RC436 WG9</th>
<th>Pump On</th>
<th>Pump Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit@1531nm</td>
<td>R Loss(dB)</td>
<td>K</td>
</tr>
<tr>
<td>12</td>
<td>53%</td>
<td>14</td>
</tr>
</tbody>
</table>

As Table XXVII shows, the round trip loss with pump on is 12 dB, and the round trip loss with pump off is 14 dB. The round trip losses are high. The difference of the round trip losses are from the Er gain and absorption. The typical ring round trip without Er is 5-7dB, the higher loss here may come from the Er bump which ring comes across it which is shown in Fig. 79.

The results have been improved by using stepper aligner in Penny State University (PSU). The ring responses are shown in Fig. 83 when pump is on and Fig. 84 when pump is off.

Table XXVIII. RC543 ring parameters.

<table>
<thead>
<tr>
<th>Ring Parameters</th>
<th>Ring Round Trip (cm)</th>
<th>Measured FSR (wavelength, nm)</th>
<th>FSR (frequency, GHz)</th>
<th>Er region length (nm)</th>
<th>Forward Pump (mW)</th>
<th>Backward Pump (mW)</th>
<th>SiO₂ Thickness (nm)</th>
<th>Q-factor (Δf=0.03GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC 543 WG6</td>
<td>2.65</td>
<td>0.03651</td>
<td>4.77</td>
<td>5</td>
<td>59</td>
<td>85</td>
<td>0</td>
<td>6.53 x10⁶</td>
</tr>
</tbody>
</table>

Ring parameters are listed in Table XXVIII. The fitted magnitude and phase responses are plotted in Fig. 85.
Fig. 83. Ring response when pump on (RC534, air cladding).

Fig. 84. Ring response when pump off (RC534, air cladding).
Table XXIX. RC543 fitted results.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Pump On/Off</th>
<th>Round Trip Loss (dB)</th>
<th>Propagation Loss (dB/cm)</th>
<th>Coupling Ratio</th>
<th>Pole</th>
<th>Zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>1547.9</td>
<td>On</td>
<td>-4.9851</td>
<td>1.88</td>
<td>0.4398</td>
<td>0.5833</td>
<td>1.0413</td>
</tr>
<tr>
<td></td>
<td>Off</td>
<td>-8.0475</td>
<td>3.04</td>
<td>0.4310</td>
<td>0.5044</td>
<td>0.8866</td>
</tr>
<tr>
<td>1550</td>
<td>On</td>
<td>-4.4245</td>
<td>1.67</td>
<td>0.5004</td>
<td>0.5666</td>
<td>1.1340</td>
</tr>
<tr>
<td></td>
<td>Off</td>
<td>-5.8492</td>
<td>2.21</td>
<td>0.4861</td>
<td>0.5351</td>
<td>1.0413</td>
</tr>
</tbody>
</table>

The Table XXIX listed the fitted results include ring round trip loss and coupling ratio calculated by poles and zeros.
From Table XXIX, the ring round trip loss at 1550nm is 4.42dB. The Erbium bump induced loss is not as large as we thought. I will keep measuring it with different thicknesses of SiO₂ cladding to see if the ring response can shift to 1531nm.

Other observations during the measurement are list below:

(1) The Er fluorescent (green light):

In the Er region when pumped, the area at the center of the coupling region is darker (Fig. 86) than the sides even when it has only backward pump. I think it means that the pump light can also coupled into the ring.

Fig. 86. Er luminescence with backward pump on: Darker in the center.

(2) Gain and absorption loss.

I can estimate the expected absorption for the length (0.5cm) and wavelength (1550nm) from some of your prior results.
From my previous results, the gain/absorption≈1:3 for every wavelength. So the gain=1/4 (RL_{pump\_on}-RL_{pump\_off}) and absorption=3/4 (RL_{pump\_on}-RL_{pump\_off}).

RT=round trip loss

For Table XXIX, the fitted ring result for air cladding, the gain at 1550nm would be:

\[
\text{Gain} = \frac{1}{4} (5.8492 - 4.4245) = 0.3562 \text{dB}
\]

\[
\text{Gain/dB} = \frac{0.3562 \text{dB}}{0.5 \text{cm}} = 0.71 \text{dB/cm}
\]

\[
\text{Absorption} = \frac{3}{4} (5.8492 - 4.4245) = 1.068 \text{dB}
\]

(3). The resonance shift between pump on and off are possibly due to the temperature drift.

I think the temperature drift will give the wavelength a tiny shift although it is very small since I measured the sample with pump on/off consecutively. It requires the temperature control it.

(4). The As$_2$S$_3$ ring has about 1μm overlap with the Ti bump which is observed by the microscope.

5.3. Er doped Ti: LiNbO$_3$ cavity

5.3.1. Multilayer measurement

Since the gain in As$_2$S$_3$ ring is hard to compensate the loss for now, another Gires Tournois structure has been carried out.
Fig. 87. Ring and GT structure.

Fig. 88. Ring and GT structure comparison.

**Ring Resonator**

\[ L = 2\pi R \]

\[ \phi \]

**Gires-Tournois Interferometer**

\[ |\rho_1| < 1 \]

\[ |\rho_2| \geq 1 \]

\[ L / 2 \]

- **Unit Delay**
  \[ T = n_g L / c \]

- **Free Spectral Range**
  \[ FSR = 1 / T \]

- **Periodic frequency response (Free Spectral Range = one period)**
- **For a lossless filter, magnitude response = 1 (allpass!)**

In Fig. 87 and Fig. 88, the right side is so called “Gires-Tournois” structure. It includes partial reflector on the left side and a total reflector on the right of the cavity. It has the same feedback structure the ring. The partial reflector works as the coupler to divide light to two paths. The difference is we already can get good gain the feedback loop in the cavity. So if we can make good reflectors on both side of the polished edge of the sample, we can achieve the ideal lossless feedback filter response.
To achieve this, we have to make a reflection at the edge of the samples. Measurement steps are shown in Fig. 89:

![Fig. 89. Reflection measurement steps.](image)

The reflection measurement for Multilayer cavity samples must add in a time domain filtering for the polarizer’s references. Because the reflected from the first surface of the polarizer has no polarization information and it is the noise. The unfiltered references will bring in noise in the data (Fig. 90, Fig. 91 and Fig. 92)
Fig. 90. TE and TM SUM out unfiltered insertion loss.

Fig. 91. TE to TE unfiltered insertion loss.

Fig. 92. TM to TM unfiltered insertion loss.
Then the polarizer’s data have been filtered in time domain by matlab code (Appendix A) to remove the first peak reflected which was reflected from the first surface of the polarizer (Fig. 93). Then the filtered references without noise in the data are shown in Fig. 94, Fig. 95 and Fig. 96.

Fig. 93. Time Domain filtering.

Fig. 94. TE and TM SUM out filtered insertion loss.
From the Figures above, the filtering can effectively remove the noise in the polarization references. And these references can be used to get the round trip loss.
RC283 is a planar diffused Er sample with multilayer deposited on the edge, H+L+H+L+H on the right edge, H on the left edge (H=As$_2$S$_3$, L= SiO$_2$, $\lambda/4$ thicknesses). It was measured when pump on and off (Fig. 97). The pump power is 85mW. The ring responses with pump on and off are shown in Fig. 98 and Fig. 99. The fitted resonant response is fitted as shown in Fig. 100 and Table XXX.

Fig. 97. Photo of RC283 at multilayer cavity measurement.
Fig. 98. RC283 multilayer result when pump on.

Fig. 99. RC283 multilayer result when pump off.
Table XXX. RC283 cavity fitted results.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Pump On/Off</th>
<th>Round Trip Loss (dB)</th>
<th>Coupling Ratio</th>
<th>Pole</th>
<th>Zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>1531_TM</td>
<td>On</td>
<td>-18.0992</td>
<td>0.9581</td>
<td>0.0828</td>
<td>1.9771</td>
</tr>
<tr>
<td></td>
<td>Off</td>
<td>-25.1165</td>
<td>0.9877</td>
<td>0.0316</td>
<td>2.5707</td>
</tr>
</tbody>
</table>

5.3.2. E-beam lithography results

SEM photos are listed below from positive resist sample and negative resist sample. The single pattern is 344 μm long (0.344 μm X 1000 periods). The width is 3.5 μm at the widest part and 2.7 μm at the narrowest part on the mask.
(a) Positive resist: ZEP 520A

The SEM photos of ZEP 520A photo resist are Fig. 101, Fig. 102, Fig. 103 and Fig. 104.

Fig. 101. SEM photo: ZEP, dose 99 $\mu$C/cm$^2$, lower amplification.
Fig. 102. SEM photo: ZEP, dose $81 \mu$C/cm$^2$.

Fig. 103. SEM photo: ZEP, dose $99 \mu$C/cm$^2$. 
Compare Fig. 102~Fig. 104, the dose 117 μC/cm\(^2\) has the best shape: the etched and remained teeth have the same width: 50% to 50%, duty Cycle=0.5.

(b) Negative resist: NEB 31A3

The SEM photos of NEB 31A3 photo resist are Fig. 105, Fig. 106, Fig. 107 and Fig. 108.

For NEB (negative resist) photos (Fig. 106~Fig. 108), all of them have blurred edges. These could be the thinner edges which are over etched. It may come from the under exposure. To conclude, dose 14 μC/cm\(^2\) has the best pattern.
Fig. 105. SEM photo: NEB, dose 14 μC/cm², lower amplification.

Fig. 106. SEM photo: NEB, dose 10 μC/cm².
Fig. 107. SEM photo: NEB, dose 12μC/cm².

Fig. 108. SEM photo: NEB, dose 14μC/cm².
CHAPTER VI
CONCLUSION

To conclude, hybrid integrated waveguide devices have been simulated, analyzed and fabricated for the gain improvement through their propagation paths. The combination of the As$_2$S$_3$ waveguides and Er doped Ti:LiNbO$_3$ waveguides have been detailed studied.

We analyzed the gain improvement for various straight overlay geometries by relating the optical mode and Er overlap to the optical propagation gain. The optimal overlay thickness was found and confirmed by experiment. The propagation gain improved from 1.1 to 2 dB/cm at 1531 nm for the TM mode. This approach is compatible with vertical integration of high-index waveguides, with application to ring resonator-based filters where the roundtrip losses may be compensated with gain.

As second hybrid device, an As$_2$S$_3$ racetrack ring resonator on top of an x-cut y-propagation Er:Ti:LiNbO$_3$ waveguide has been designed and fabricated. The ring was side-coupled with the Ti:LiNbO$_3$ waveguide and the optical gain was achieved 0.72 dB/cm when the Er doped coupling region was pumped by 144mW pump laser. The free spectral range (FSR) of the measured ring response for TM mode is 0.0587nm (7.33GHz) at 1550nm. The roundtrip loss are 4.4dB when pump on and 5.8dB when pump off.

The Er doped cavity has also been studied. The back mirror was fabricated by multilayer dielectric films consists of three As$_2$S$_3$ layers and two SiO$_2$ layers, with
reflectivity 82% at 1531m by simulation. The front partial reflector was designed to be a double-side Bragg grating using As$_2$S$_3$. The period was designed at 344 nm to make the central frequency of the reflection spectrum is at 1531nm. The fabrication of As2S3 grating was achieved by E-beam lithography due to its tiny structures. The align mark design and mask making which allows the alignment between As$_2$S$_3$ gratings and Ti diffused waveguides have been finished and the samples’ testing results are coming out soon.
REFERENCES


APPENDIX A

MATLAB CODES FOR TITANIUM DIFFUSION PARAMETER CALCULATION AND TIME DOMAIN FILTERING

Matlab code for titanium diffusion parameter calculation:

```matlab
%% delta RIN (Refractive Index change)
clear;
%%%%% Input parameters: %%%%%%%%%%%%
t_h=9.5;     % diffusion time by hours
tal=0.095;   % Ti strip thickness: um->cm%
w=7;         % Ti strip(waveguide) width: um
T=1298.15;   % diffusion temperature=1025 degree
lamda=1.55;  % um
%%%%% End of Input parameters %%%%%

%%%%%%% Constants %%%%%%%%%%%%%%%
T0=30300;
t=t_h*3600;
DoV_cm=0.0199; %% Diffusivity: cm^2/s => m^2/s %
DoH_cm=0.0289;
DoV=DoV_cm*1e-4;
DoH=DoH_cm*1e-4;

do=0.67*lamda^2/(lamda^2-0.13);
dc=0.839*lamda^2/(lamda^2-0.0645);
Fo=1.3e-25;  %% Fo,Fe: cm^3
Fe=1.2e-23;
gmo=0.55;
gme=1;
%%%%% End of Constants %%%%%%%%

%%%%%Diffusion Length: um %%%%%%
Dh=2*sqrt(t*DoH*exp(-T0/T))*1e6
Dv=2*sqrt(t*DoV*exp(-T0/T))*1e6

%%%%% Delta RIN %%%%%%
Cm=5.67e22;   % cm^-3
c0=tal*Cm/(sqrt(pi)*Dv);
c=c0*2*erf(w/2/Dh);
```
\[ \text{delneXX} = \text{de} \cdot (\text{Fe} \cdot \text{c})^{\text{gme}} \cdot 1.7 \]
\[ \text{delnoYY} = \text{do} \cdot (\text{Fo} \cdot \text{c})^{\text{gmo}} \cdot 1.49 \]
\[ \text{delnoZZ} = \text{delnoYY} \]

Matlab code for Time domain filtering:

```matlab
% Input filter function to filter Jpol
plot(time,abs(Jpol(1,:)).^2+abs(Jpol(2,:)).^2+abs(Jpol(3,:)).^2+abs(Jpol(4,:)).^2);
temp=input('pick two points and press enter');
n1=p1.DataIndex;
n2=p2.DataIndex;
% filter window:
window1_1=zeros(1,n1);
window1_2=ones(1,n2-n1);
window1_3=zeros(1,m+1-n2);
window1={[window1_1 window1_2 window1_3];
        window1=cell2mat(window1);
        for n=1:4
            Jpol(n,:)=Jpol(n,:).*window1;
        end
```
### APPENDIX B

#### OPTI-SYSTEM PARAMETERS

The EDWA parameters are listed below:

Table A-1 EDWA parameters setting

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Units</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide Length</td>
<td>0.035</td>
<td>m</td>
<td>Normal</td>
</tr>
<tr>
<td>Signal background loss</td>
<td>40</td>
<td>dB/m</td>
<td>Normal</td>
</tr>
<tr>
<td>Pump background loss</td>
<td>15</td>
<td>dB/m</td>
<td>Normal</td>
</tr>
<tr>
<td>Refractive index data file</td>
<td>950A Ti,9 hrs diffusion</td>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Er ion density distribution</td>
<td>Er Profile which has Deff=6um</td>
<td></td>
<td>Normal</td>
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<tr>
<td>Wavelength to calculate the mode</td>
<td>1531</td>
<td>nm</td>
<td>Normal</td>
</tr>
<tr>
<td>Polarization for signal mode calculation</td>
<td>TE or TM</td>
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<td>Normal</td>
</tr>
<tr>
<td>Number of modes at pump wavelength</td>
<td>1</td>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Polarization for pump mode calculation</td>
<td>TE or TM</td>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Power ratio for each pump mode</td>
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<td>Er ion density</td>
<td>100e24</td>
<td>m^-3</td>
<td>Normal</td>
</tr>
<tr>
<td>Er metastable life time</td>
<td>2.4</td>
<td>ms</td>
<td>Normal</td>
</tr>
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<td>Er signal excess loss</td>
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<td>dB/m</td>
<td>Normal</td>
</tr>
<tr>
<td>Er pump excess loss</td>
<td>0</td>
<td>dB/m</td>
<td>Normal</td>
</tr>
<tr>
<td>Yb ion density</td>
<td>1e0</td>
<td>m^-3</td>
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<tr>
<td>ESA cross section value at</td>
<td>55e-027</td>
<td>m^2</td>
<td>Normal</td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------</td>
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</tr>
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<td>A32</td>
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<td>1/s</td>
<td>Normal</td>
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<td>A43</td>
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<tr>
<td>Fraction of ion in pair</td>
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<tr>
<td>Fast nonradiative upconversion lifetime</td>
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<td>s</td>
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<td></td>
<td>Normal</td>
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<tr>
<td>Cup</td>
<td>10e-24</td>
<td>m^3/s</td>
<td>Normal</td>
</tr>
<tr>
<td>C3</td>
<td>100e-24</td>
<td>m^3/s</td>
<td>Normal</td>
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<tr>
<td>C14</td>
<td>70e-24</td>
<td>m^3/s</td>
<td>Normal</td>
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<tr>
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<td>m^3/s</td>
<td>Normal</td>
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</tr>
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<td>THZ</td>
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<td>THz</td>
<td>Normal</td>
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<tr>
<td>Noise bins spacing</td>
<td>125</td>
<td>GHz</td>
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<td>dB</td>
<td>Normal</td>
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<td>Noise dynamic</td>
<td>3</td>
<td>dB</td>
<td>Normal</td>
</tr>
<tr>
<td>Convert noise bins</td>
<td></td>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Generate random seed</td>
<td>Yes</td>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Random seed index</td>
<td></td>
<td></td>
<td>Normal</td>
</tr>
</tbody>
</table>
VITA

Xiaomin Song was born in Hefei, China in 1980. He received his Bachelor of Science degree in electrical engineering from Tsinghua University, Beijing, China in 2003 and Master of Science degree in electrical engineering from Tsinghua University, Beijing, China in 2006. He received his Ph.D. degree in electrical and computer engineering from Texas A&M University in 2011. His research interest involves integrated optical filter and amplifier design and fabrication.

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