Hybrid Chalcogenide Waveguide Devices for the Mid-Infrared

X. Wang, C. Zhang, Y. Zhou and C. Madsen

Texas A&M University, College Station, TX

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Overview

- Materials
- Optical filters and modulators
- Waveguide fabrication
- Waveguide measurements
- Electro-optic tuning
- 3\textsuperscript{rd}-order nonlinearity (FWM, XPM)
- 2\textsuperscript{nd}–order nonlinearity (DFG)

FWM=four wave mixing
XPM=cross phase modulation
DFG=difference frequency generation
**Lithium Niobate (LiNbO₃)**

- Uniaxial birefringence crystal
- Transmission: 0.42-5.2 µm
- Electro-optical ($r_{33} = 30.8$ pm/V)
- 2nd–order nonlinearity (DFG)
- Optical waveguide
  - low propagation loss
  - low fiber-coupling loss
  - High reproducibility

Transmittance spectrum of LiNbO₃ (FTIR)

Titanium diffused LiNbO₃ waveguide

https://www.o-digital.com
Arsenic Tri-sulfide ($\text{As}_2\text{S}_3$)

- Amorphous
- High index: 2.44 at 1.55 µm
- Transmission: 1-10 µm
- 3rd–order nonlinearity (FWM, XPM)
- Low processing temperature
- Photosensitivity

Transmittance spectrum of $\text{As}_2\text{S}_3$ (FTIR)

https://en.wikipedia.org
DC/RF Magnetron Sputtering

AJA system uses a rotating substrate and angled sputtering guns to provide excellent uniformity

- System has a loadlock
- Holds five sputtering targets

As$_2$S$_3$ Deposition Uniformity (Horizontal)
Vertically Integrated Waveguides

Uncoupled waveguide modes:
Fundamental Ti:diffused LiNbO$_3$ and As$_2$S$_3$ waveguide modes

Supermodes:
Fundamental (even) and first higher order mode (odd) of coupled waveguides

Coupling between waveguides using an As$_2$S$_3$-Ti:LiNbO$_3$ taper coupler
Ti:LiNbO$_3$ Waveguide Fabrication

High temperature and long!

Nonplanar waveguide surface
As$_2$S$_3$-only Waveguide Fabrication

- Thin film deposition
  - As$_2$S$_3$ + protective layer
- Photolithography
  - Contact aligner
- Reactive ion etching
  - CHF$_3$ + Ar
  - O$_2$ ashing
- Bonding & polishing
  - critical to obtain low insertion loss
  - bond the sample and a bare LiNbO$_3$ face to face with wax
- HF etching
  - protective layers removal
Hybrid Interferometer

A Mach Zehnder Interferometer (MZI)

- Given two different optical paths, an optical path length difference (OPD) due to the different refractive indices of the materials seen by each optical mode:

\[ \text{OPD} = n_{As_2S_3} \ell_{As_2S_3} - n_{Ti} \ell_{Ti} \]

- This optical path length difference gives a phase shift when the two optical modes are recombined:

\[ \Delta\varphi = \left( \frac{2\pi}{\lambda} \right) \text{OPD} \]
Resonant response of an ultra-narrow FSR (0.0579 nm) 1.7-cm long path fabricated As$_2$S$_3$-on-LiNbO$_3$ ring resonator [1]: 1.2 dB/cm loss, 41% coupling strength at 1.55 µm

**Electro-Optic Tuning**

- LiNbO$_3$ is an anisotropic material with electro-optic tuning based on the linear Pockel’s effect
  - Want to take advantage of strongest tuning coefficient, $r_{33}$
  - As$_2$S$_3$ waveguides originally designed for TM polarization

- Tuning with $r_{33}$ requires an optical polarization field and electrical field in the z-direction
  - TM requires electrode overlap with the waveguide
  - TE avoids electrode overlap requirement
Tunable Ring Resonator

- **Path length tuning**
  - Push mode into LiNbO3

- **Coupling region tuning**
  - Back to back tapers
  - Behaves like an interferometer

Two modes experience different electro-optic tuning strengths
Nonlinear Chirp Waveform Generator

- Modulate electro-optic electrodes with a sinusoidal drive, within the feedback path, and get non-linear frequency chirps
- A tanh() function was achieved with 86% coupling, assuming 2 dB of round trip loss
- Demonstrated 100MHz modulation

Simple drive signal, complex waveform generation
MZI-Ring Frequency Discriminator

- MZI: TE/TM path in-between two Polarization Converters
- MZI FSR=175GHz, Ring FSR=7.25 GHz
- TM-only Ring response
- $24 \times \text{FSR}_{\text{ring}} = \text{FSR}_{\text{MZI}}$

$n_x = n_o = 2.2112$

$c = 1.85 \text{cm} \quad \text{FSR} = 7.25 \text{GHz}$

$n_z = n_e = 2.1384$

$\text{BW} = 4.83 \text{GHz}$
**Near-IR Optical Measurements**

- **Optical Vector Analyzer**
- **Tunable Laser**
- **Single mode fiber**
- **Polarization-resolved Linear swept-wavelength Complex frequency response**
- **Insertion Loss**

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M. Solmaz, “Integration of arsenic trisulfide and titanium diffused lithium niobate waveguides”, PhD dissertation, Electrical Engineering, Texas A&M University, College Station, 2010.
**Mid-infrared Sidewall Grating Design**

**Grating period:**
- $\Lambda = 480$ nm (ease of fabrication)

$$\Lambda = \frac{\lambda}{2n_{\text{eff}}} = \frac{2050 \text{ nm}}{2 \times 2.143730717} = 478.1384 \text{ nm}$$

$W_0 = 3.8 \mu m; \ t = 380 \text{ nm}$

$A_{\text{eff}} = 5.19 \mu m^2$

$n_{\text{eff}} = 2.1437$

$CF = 0.345$

**Applications:**
- Optical filters (phase-shift, coupled phase shift, EO-tunable, add-drop and WDM)
- Resonance cavities with high-Q values for nonlinear enhancement, and amplification in lasers
- Sensing (refractive index sensor, biosensor)

**Virtue:**
- Easy control of grating corrugation profiles
- Low-loss fiber coupling, capabilities for integration
- Simple fabrication
Reflectance of mid-infrared gratings

Flat-top narrowband transmission filters by cascading phase-shifted gratings.
Cascaded phase-shifted gratings

Transfer matrix method:

\[
T_i = \begin{bmatrix}
\cosh(\delta L_i) - j \frac{\Delta \beta}{2 \delta} \sinh(\delta L_i) & -j \frac{\kappa}{\delta} \sinh(\delta L_i) \\
-j \frac{\kappa}{\delta} \sinh(\delta L_i) & \cosh(\delta L_i) + j \frac{\Delta \beta}{2 \delta} \sinh(\delta L_i)
\end{bmatrix}
\]

\[
\Delta \beta = 2 \beta - \frac{2 \pi}{\Lambda} \quad \delta = \sqrt{\kappa^2 - \left(\frac{\Delta \beta}{2}\right)^2} \quad \beta = \frac{2 \pi}{\lambda} n_{\text{eff}} + j \alpha
\]

\[
L_i = \begin{cases} 
N_i \Lambda & \text{for uniform grating} \\
\Lambda / 2 & \text{for phase-shift spacer}
\end{cases}
\]

\[
T_{\text{total}} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \prod_i T_i
\]

\[
R = \left| \frac{T_{21}}{T_{11}} \right|^2 \quad T = 1 - \left| \frac{T_{21}}{T_{11}} \right|^2
\]
As$_2$S$_3$ Grating Coupler Cavity

(a) Cross section view of the hybrid As$_2$S$_3$-on-LiNbO$_3$ waveguide;
(b) Mode intensity distribution of the hybrid waveguide;
(c) Test structure of a single sidewall grating coupler;
(d) Zoom-in view of the sidewall grating structure
Sidewall Grating Cavities

- Place a straight waveguide in between two uniform gratings
  - High Q-factor of $10^6$
  - Small free spectral range (FSR)
  - Nonlinear enhancement

$$FSR = \frac{\lambda^2}{2n_{eff} L_{eff}}$$

(a) Electrical field enhancement inside the grating cavity waveguide
(b) Sidewall grating cavity resonant response at the wavelength from 1547.5~1552.5 nm;

\[ \text{Enhancement} = \frac{|E|^2}{|E_{in}|^2} \]
**E-beam lithography for As$_2$S$_3$ gratings**

1. X-cut LiNbO$_3$
2. As$_2$S$_3$
3. SiO$_x$
4. PMMA Resist
5. After exposure and developing
6. E-beam evaporation of Cr metal
7. CHF$_3$ and Ar plasma RIE etching
8. Lift-off resist and Cr
9. HF dipping
10. As$_2$S$_3$
11. X-cut LiNbO$_3$
12. Chromium, LiNbO$_3$ channel waveguide
Electron-beam Lithography Process

D = 200 uC/cm²

D = 250 uC/cm²

D = 300 uC/cm²

D = 400 uC/cm²

D = 350 uC/cm²

D = 300 uC/cm²
As$_2$S$_3$ Grating and Taper

X. Wang et al., “Fabrication and measurement of sidewall gratings integrated in hybrid As$_2$S$_3$-Ti:LiNbO$_3$ optical waveguides,” IEEE, J. of Lightwave Technol., 2014 (accepted).
- Fitted coupling coefficients agree well with analytical calculations.

X. Wang et al., “Fabrication and measurement of sidewall gratings integrated in hybrid As$_2$S$_3$-Ti:LiNbO$_3$ optical waveguides,” IEEE, J. of Lightwave Technol., 2014 (accepted).
Near-IR Phase-shifted Gratings

- Narrow-bandwidth transmission peak: 0.25 nm
- Phase-shift spacer (a micro-cavity): $\lambda/2$
- Q-factor is limited by coupling coefficient ($\sim6200$ for $N = 1200$)

X. Wang et al., “Fabrication and measurement of sidewall gratings integrated in hybrid $\text{As}_2\text{S}_3$-$\text{Ti}:\text{LiNbO}_3$ optical waveguides,” IEEE, J. of Lightwave Technol., 2014 (accepted).
(a) Reflection and transmission of a single sidewall grating coupler; (b) Sidewall grating cavity resonator response; (c) A zoom-in plot of the resonant response at 1547~1553 nm wavelength range
Measurement and Fitting Results

Measurements and fittings of (a) reflection of a single grating coupler; (b) reflection and (c) transmission of a sidewall grating cavity

Fitting: coupling strength: 14 mm\(^{-1}\)
Propagation loss inside the cavity: 2.5 dB/cm
• Electro-optical tuning rate (~4 pm/V for d = 10 µm)

\[ E_z = \frac{V_a}{d} \]

\[ \Delta n_e = -\frac{1}{2} n_e^3 r_{33} E_z \]

- \( V_a \): applied voltage
- \( n_e \): extraordinary index of LiNbO₃ (\( n_e = 2.2 \))
- \( d \): gap distance between electrode
- \( r_{33} \): EO coefficient, \( 30.8 \times 10^{-12} \text{m/V} \) for x-cut, y-propagation LiNbO₃ substrate.

Fabricated mid-infrared gratings

Two-stage taper:
- tip: 600 nm
- length #1: 300 um
- transit width: 2.5 um
- length #2: 100 um

Sidewall grating:
- depth: 1.2 um
- period: 480 nm
- width: 4.6 um
Experimental Measurement Setup

Supercontinuum source (NKT photonics):
- Wavelength range: 440-2400 nm
- Repetition rate: 24 kHz
- Total output power: ~100 mW

OSA (Thorlab):
- Wavelength range: 1000-2500 nm
- Spectral resolution: 7.5 GHz (0.25 cm⁻¹, corresponding to 105 pm @ 2050 nm)
- Maximum OPD: ±4 cm
S/C Source Measurement Setup

![Graph showing transmittance in dBm vs. wavelength for Ti waveguides and fiber-to-fiber connections.](image)

- **Wavelength (nm)**: 1000 to 2500
- **Transmittance (dBm)** ranges from -90 to -10 dBm

Legend:
- Pink: Ti waveguide #1
- Blue: Ti waveguide #2
- Orange: Fiber to fiber
- Pink: Laser off

**Waveguide Configurations**:
- Ti waveguide #1
- Ti waveguide #2
- Fiber to fiber connection
- Laser off

**Additional Notes**:
- Image shows a lab setup with various components and measurements.
- The graph indicates the transmittance properties across different wavelengths for various configurations.
Nonlinear Applications of Chalcogenide waveguides

\[ n(\omega, I) = n_0(\omega) + n_2 I(t) \]

Self-phase modulation based integrated all-optical signal regenerations[1]

All-optical wavelength conversion via cross-phase modulation in As2S3 rib waveguide [2]

Active Ring Applications

Through tuning the effective refractive index of the mode inside the ring waveguide, ring resonator based on-chip active devices can realize various functions, such as modulators, reconfigurable optical filters and all-optical switchers.

\[ \phi_{NL}(t) = (2\pi/\lambda)n_2I(t)L \]

A 12.5 Gbit/s carrier injection silicon ring modulator [1]

An all-optical self-phase modulation based tunable As2S3 racetrack ring resonator [2]

[2]. Hu et al, OPTICS LETTERS / Vol. 35, No. 6 / March 15, 2010
Nonlinear Measurement for XPM

λ1 ~ λ2

Signal Agilent Laser

Pump HP laser

EDFA

λ0, resonant wavelength

PC: polarization controller

TEC box

Thermal-electrical controller

Pass λ1~λ2, block λ0

Band-stop filter

2%:98%

Fiber coupler

Power meter

Photo-diode detector

Computer Labview
Measurement Setup

Bandpass filter
Photodiode detector
CW signal laser
Polarization controller
EDFA
Pump laser
Polarization paddles
Combiner/Splitter
TEC box
Bandpass filter
Photodiode detector
Signal: 5 mW
-16 dB
0 dB
Pump: 100 mW

- Both signal and pump are TM polarization.
- Signal scanning range: 1554.5~1555.5 nm
- Pump wavelength: 1564.902 nm
- Bandpass filter: 1552~1557 nm
FOUR-WAVE MIXING

A third-order nonlinear process

- Interactions between two wavelengths produce two new wavelengths

★ Energy $\omega_1 + \omega_2 = \omega_3 + \omega_4$
★ Momentum $\beta_1 + \beta_2 = \beta_3 + \beta_4$

➢ Degenerate FWM

- Single pump: $\omega_1 = \omega_2$
- Input: pump, signal
- Output: pump, amplified signal, idler

$$2\omega_p = \omega_s + \omega_i$$
FWM Down-Conversion Design

- Generation of 3.03 µm mid-IR light
  - Signal: 1.55 µm
  - Pump: 2.05 µm
- Dispersion engineering
- Phase-matching condition
  \[
  \Delta \kappa = 2\pi \left( \frac{n_s}{\lambda_s} + \frac{n_i}{\lambda_i} - 2 \frac{n_p}{\lambda_p} \right) + 2\gamma P_p
  \]
- Parametric conversion efficiency
  \[
  G_i = \frac{P_i(L)}{P_s(0)} = \left[ \frac{\gamma P_p}{g} \sinh(gL_{eff}) \right]^2
  \]
**Simulation Results**

**Phase mismatch**

- \( w = 1.4 \mu m \) \( h = 1.7 \mu m \) with 0.18 \( \mu m \) MgF\(_2\)

**Parametric conversion efficiency**

- -8 dB when \( P_p = 0.1 \text{GW/cm}^2 \)
- -28 dB when \( P_p = 0.01 \text{GW/cm}^2 \)
Electrical signal-to-noise ratio improvement in indirect detection of mid-IR signals by FWM up-conversion

- Signal: 4.6 μm (mid-IR)
- Pump: 2.05 μm
- Idler: 1.32 μm (near-IR)
eSNR IMPROVEMENT

- $eSNR_{\text{near-IR}} / eSNR_{\text{mid-IR}}$

Comparison to PbSe

Comparison to MCT

Graphs showing the eSNR improvement (dB) with respect to pump power intensity (GW/cm²) for different intensities (0.1µW, 1µW, 10µW) compared to PbSe and MCT.
## COMPARISON TO Si WAVEGUIDES

<table>
<thead>
<tr>
<th>WG type</th>
<th>Mid-IR signal</th>
<th>Near-IR idler</th>
<th>$P_{in}(\mu W)$</th>
<th>PbSe(dB)</th>
<th>MCT(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As$_2$S$_3$</td>
<td>4.6 µm</td>
<td>1.32 µm</td>
<td>0.1</td>
<td>67</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>51</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>29</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si*</td>
<td>4 µm</td>
<td>1.55 µm</td>
<td>0.1</td>
<td>50</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>37</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>27</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- More effective for weak mid-IR signals

FWM Measurement Setup

- Black diamond lenses
  - focusing the beam to As$_2$S$_3$ waveguide: 0.2 dB coupling loss for pump by Zemax
  - re-collimating the output beam
- Fourier transform infrared spectroscopy
  - detection to the output wavelengths
  - 0.5 nm resolution
No idler wavelength generated
  • Phase-matching condition is not met?
  • Pump power is not sufficient?
Mid-Infrared Amplitude and Group Delay Measurements

LOW COHERENCE INTERFEROMETRY
INTERFERENCE PATTERN

\[ I(\tau) = \frac{1}{2} \int_0^\infty |A(f)|^2 A(f) \cos[\phi(f) - 2\pi f \tau] df \]

- DC terms neglected
- A(f): ASE spectral density
- \( \Phi(f) \): DUT phase response
- \( \tau \): x/c
Optical Sampling Signal

Laser interference pattern

ASE interference pattern

\( \lambda_{\text{laser}} \)

Laser fringe patterns

\( x 10^{-3} \)

Amplitude

Time (s)
Baseline FRINGE PATTERN & SPECTRA

FBG fringe pattern

Spectra

FBG fringe pattern

Spectra
FWM Device Status

Design
- FWM down conversion
- FWM up conversion

Fabrication
- As$_2$S$_3$-on-LiNbO$_3$ waveguides for FWM down conversion

Measurement
- FWM measurement
- Phase matching or pump power issue

Characterization
- OLCI system verification
- OLCI for mid-IR
Mid-infrared DFG Waveguide

- DFG (difference-frequency generation)
  - Pump wave: TM, 1.42 µm
  - Signal wave: TE, 2.05 µm
  - Idler wave (DFG output) near 4.745 µm

- Conversion efficiency
  - Material nonlinearity
  - Phase mismatch
  - Tight mode confinement
  - Low propagation loss

\[
\eta = \frac{P_i}{P_P P_s} = \left(\frac{2\pi c}{\lambda_i}\right)^2 \cdot \exp[-(\alpha_p + \alpha_s + \alpha_i)L/2]
\]

\[
\kappa = d_{\text{eff}} \sqrt{2\mu_0/(c n_p n_s n_i A_{\text{eff}})}
\]

\[
\Delta \beta = 2\pi \left(\frac{n_{\text{eff}}^p}{\lambda_p} - \frac{n_{\text{eff}}^s}{\lambda_s} - \frac{n_{\text{eff}}^i}{\lambda_i}\right)
\]
Output Idler Powers and Efficiency

- At $L = 16$ mm, $P_p = P_s = 150$ mW, the output idler
  - Power: $P_i = 3.6$ mW
  - Linewidth: $\Delta \lambda = 0.46$ nm
  - Noise: $\sim 1$ nW (SNR $> 10^6$)

- Optimal conversion efficiency is $20.52\% W^{-1}$ at $L = 26$ mm
- Beyond 26 mm, the efficiency is limited by waveguide loss
Conclusions

- Novel mid-infrared source using DFG (X. Wang)
- Electron-beam lithography process for single layer waveguides (Y. Zhou and X. Wang)
- Grating device design (X. Wang)
- Mid-infrared filter measurements using OLCI (C. Zhang)
- Broadband FWM device design (Q. Chen)
- Resonant-enhanced nonlinear switch (Y. Zhou)
- Electro-optic tuning – frequency discriminator (J. Kim)