High-Efficiency Asymmetric Transmission of Circularly Polarized THz waves using a Dielectric Herringbone Metasurface

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• Primary Objective
• Motivation & Background
• Design
• Simulation & Analytical results
• Fabrication
• Experimental Results
• Conclusion and Future Prospects
• Achieve **Asymmetric Transmission** (or **Conversion Circular Dichroism**) in THz regime using **dielectric** metasurface.

• Based on combination of **Geometric phase** (Pancharatnam-Berry Phase) and **Dynamic phase**.

→ Interference between the two phase mechanisms.
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2D chiral media, e.g. meander/asymmetric split ring
Conversion Circular Dichroism (asymmetric transmission), fully flips one handedness, prevents the other (reflection)
• Previous designs use metal structures → lossy!

• For single layer designs, small conversion efficiency → intrinsic mechanism only allows less than 25% conversion.

• Multilayer designs have better efficiency (53%), but still lossy (37% loss) and involve complex designs/fabrication [Pfeiffer et al.]

• Need to develop a ‘trivial’ method of achieving this phenomenon...
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Half wave-plate → using Subwavelength Gratings (SWG’s)
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Step 2: Introduce phase disparity between handedness’ → Geometric Phase

Pancharatnam–Berry Phase! \( \varphi_{\text{Geometric}} = \pm 2\theta \) (‘+’ RCP / ‘−’ LCP)

Phase difference between two structures. e.g. \( \theta = \pi/4 \), so, \( \varphi_{\text{Geometric}} = \pm \pi/2 \).
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**Step 3: Introduce a fixed dynamic phase between the two structures**

\[ \varphi_{Dynamic} = \Delta n_{Si-Air} (2\pi d/\lambda) \rightarrow \text{need to get d, the elevation height} \]

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• Designed structure is analogous to using birefringent crystals

• Use Subwavelength gratings for half-wave plate:
  → Period condition is: $\Lambda \leq \lambda / n_{II}$

$\Lambda$ is period, $\lambda$ is free-space wavelength, $n_{II}$ is refractive index of substrate

→ Want to perform at 1 THz, use silicon (10kΩ):
  $\lambda = 300 \, \mu m$, $n_{II} = 3.418 \rightarrow \Lambda \leq 87.7 \, \mu m$

Choose $\Lambda = 86 \, \mu m$
• Need to calculate depth and duty-cycle of SWG’s.

Grating equation: \[ \Delta \Phi_{TE-TM}(\lambda) = \left(\frac{2\pi h}{\lambda}\right) \Delta n_{form}(\lambda) \]

• \( \Delta \Phi_{TE-TM} \) is the (wavelength-dependent) phase difference between parallel (TE) and perpendicular (TM) components of light in the grating.

• \( h \) is the depth of the gratings

• \( \Delta n_{form} \) is the difference in refractive indices along the TE and TM directions of the grating, given as:

\[ \Delta n_{form} = n_{TE}(\lambda) - n_{TM}(\lambda) \]

\[ n_{TE} = \left( F n_1^2 + (1-F) n_{II}^2 \right)^{1/2} \]

\[ n_{TM} = \left( F n_1^{-2} + (1-F) n_{II}^{-2} \right)^{-1/2} \]

• Using a duty cycle of \( F = 0.5 \), and \( n_I = 1 \) for air, we have:

\[ n_{TE} = 2.52 \quad n_{TM} = 1.36 \quad \Delta n_{form}(\lambda) = 1.16 \]
\[ \Delta n_{form}(\lambda) = 1.16 \quad \Rightarrow \quad \Delta \phi_{TE-TM}(\lambda) = \left(\frac{2\pi h}{\lambda}\right) \Delta n_{form}(\lambda) \]

- Want Half-wave plate functionality, choose \( \Delta \Phi = \pi \)

Rearrange to get \( h = 129 \, \mu m \)

- Apply P-B phase of \( \pi/2 \) by setting \( \alpha = 22.5^\circ \)

- Apply dynamic phase of \( \pi/2 \) by adding a step beneath one grating, need to calculate step height \( d \)

Use equation: \[ \Delta \varphi_{Dyn} = \Delta n_{Si-Air} \left(\frac{2\pi d}{\lambda}\right) \]

Simply get \( d = 31 \, \mu m \)
• Simulate using CST Microwave studio

• Very high cross polarisation, $T_{RL} \approx 85\% @ 1.05\text{THz}$

• $T_{LR}$ is low (15\% @ 1.05\text{THz}) as required

• Unconverted (co-pol.) values are low, <10\% @ 1.05\text{THz}
• Use analytical model based on Fresnel’s equations for a three-layer system.

\[ t_i = \frac{t_{12i} t_{23i} e^{-i\phi}}{1 + r_{12i} r_{23i} e^{-2i\phi}} \]

\[ \phi_i = \frac{2\pi d}{\lambda} n_{2i} \]

\[ t_{12i} = \frac{2n_1}{n_1 + n_{2i}} \]

\[ t_{23i} = \frac{2n_{2i}}{n_{2i} + n_3} \]

\[ r_{12i} = \frac{n_1 - n_{2i}}{n_1 + n_{2i}} \]

\[ r_{23i} = \frac{n_{2i} - n_3}{n_{2i} + n_3} \]

• Use this equation to describe yellow SWG without phases

• Introduce P-B and dynamic phases to 2\textsuperscript{nd} blue SWG, sum the two transmittances together:

\[ T = n_3 \left| \frac{1}{2} (t + t \cdot e^{i\Phi_Dyn} \cdot e^{i\Phi_{Geom}}) \right|^2 \]
• Similar results to simulation
• Very high cross polarisation, $T_{RL} \approx 85\% @ 1.1\text{THz}$
• $T_{LR}$ is low ($\sim 1\% @ 1.1\text{THz}$)
• Unconverted (co-pol.) values are low, $<1\% @ 1.1\text{THz}$
• Slight mismatch in central frequency and design of 1 THz

→ SWG’s are based on 1\textsuperscript{st} order effective medium theory, period actually \( \sim 80 \mu \text{m} \)
→ Fabry- Pérot effects between layers, differs from single-pass theory
→ SWG’s & step not dispersionless, operation changes for wavelength
• Standard photolithography and Deep Reactive Ion Etching used to fabricate silicon wafer

• First, stripes of 31 μm step are fabricated by etching

• Then, zig-zags overlaid, and etched down 129 μm.
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• Slight difference between bottom step and top step (red circles) ➔ Re-simulate to reflect this
• Simulation not too different to previous ‘desired’ parameters

• THz-TDS (Time Domain Spectroscopy) used to obtain experimental data. → Linear polarisation, post-processing to convert to circular basis

• Experimental result impressive → \( T_{RL} \approx 63\% \) @ 1.025THz → \( T_{LR} \approx 13\% \) → Extinction ratio approx. 5:1

• Un-converted polarisations are <20%

• Difference between exp. & sim. due to fabrication errors, step mismatch, and side-wall slope, material losses
• Very broadband, FWHM of 0.72 THz at central frequency of 1.025 THz \( \Delta f/f = 70\% \)

• Total energy, \( T_R \) and \( T_L \):
  \( T_R = 28\% \)
  \( T_L = 84\% \)

• \( R = 1 - T \) (ignore absorption)
  \( \Rightarrow \) Implies that \( R_R \) is 72\%

• The device can be used to distinguish between L and R to a high efficiency
Achieved Asymmetric Transmission/Conversion Circular Dichroism using dielectric metasurface, not metallic.

Straight-forward approach, rather than trial-and-error optimization of impedances between layers etc...

Obtained highest recorded AT of 63% (to our knowledge) in the THz regime (possibly all regimes).

Very broadband, $\Delta f/f = 70\%$, and extinction ratio of 5:1 between $T_{RL}$ and $T_{LR}$.

TL = 84% and RR = 72%, can use device to distinguish handedness of incident light to high efficiency.
Potential for use in other frequency regimes

Dielectric nanobricks, e.g. TiO$_2$ for visible light, act as half-wave plates
- incorporate extra phase step beneath opposing element to induce handedness dependence

Could have holograms which only operate for one handedness, have holographic image in different quadrants in $+Z$ and $-Z$ axis

Linear-to-circular lenses, using P-B phase with only one foci, not two
Thank you
• Duty cycle, $F = 0.5$
• $\Lambda = 86$ $\mu$m, not quite equal to actual period of gratings  
  $\rightarrow$ actual period $\sim 80 \mu$m
• $W = 208$ $\mu$m, due to geometry
Subwavelength Gratings
• Grating not too different to ‘desired’ bulk parameters
  → approx. π phase difference → Half-wave plate
Fabrication

Photomask

1st Pattern to etch - STRIPES

2nd Pattern to etch - ZIGZAGS
**Fabrication**

**Procedure**

1. **Clean intrinsic silicon**
2. **Spincoat (8μm) SPR220-7 onto silicon**
3. **Use STRIPE pattern of mask to expose**
4. **Etch into the silicon using DRIE**
5. **Remove SPR220-7**
6. **Spin on ~50μm of SU8-2000**
7. **Use ZIGZAG pattern, to expose, then develop and Etch down 130μm**
8. **Remove SU8 (piranha)**