Planar diffractive optical elements for THz beam polarization control

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Waveplates

- Waveplates, or phase retarders, are the essential devices for manipulating and controlling the polarization state of EM radiation.
- Waveplates introduce a controlled phase delay between two orthogonal polarization components, enabling modulation of EM wave properties via change of the polarization state.

Birefringence

- Birefringence is an optical phenomenon that occurs when a light passes through a specific material experiences different refractive indices for different polarizations of light, where each polarization component propagates with a different speed.
- Eg: Liquid crystals, Crystalline quartz, and $LiNbO_3$
- These natural birefringence materials are very limited in the THz regime due to the low birefringence, large loss, bulk in size, and high price.

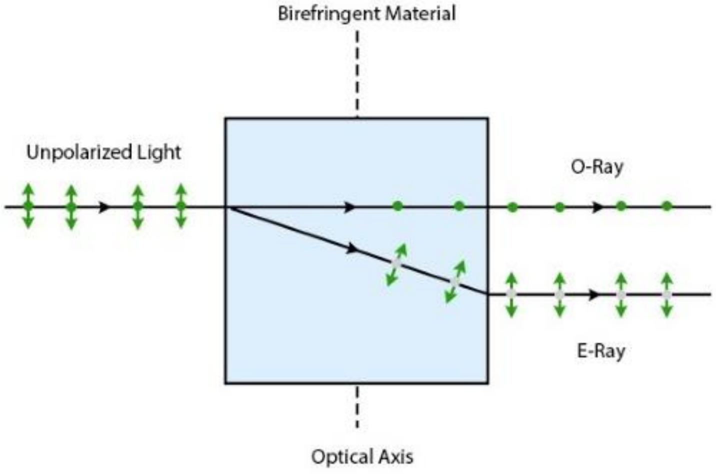

Fig.1. Scheme of Birefringence inside a birefringence material

https://www.gophotonics.com/community/what-is-birefringence

Artificial birefringence

- One way to create an artificial birefringence is by creating a subwavelength grating on the materials.
- These structures are made by etching or ablating small grooves leaving as a result of air and material periodic sequence on a dielectric/metal substrate.
- Materials like Silicon and Polymers such as HDPE and Teflon have small losses at THz frequencies which could make them a suitable material choice.
- Silicon gets a top pick in hand because of its high thermal stability, more transparent with minimal absorption losses, Low dispersion across the THz frequencies.

Recent progress on THz waveplate

Materials Classification	Materials Types	Bandwidth /THz	Advantages	Disadvantages
Natural Materials	Lithium Niobate	0.90	1.Large birefringence	1.High absorption 2.Brittle
	Quartz	0.10	1.High transmittance	1.Low birefringence
Gratings	Metal-based	0.60	1.High phase modulation	1.High absorption 2.Reflection losses
	Dielectric -based	0.40	1.Low loss 2.High phase modulation	1.More fragile 2.Less thermal stability
Metamaterials	Metal-insulator-metal	0.52	1.High transmission efficiency 2.Low insertion losses	1.Complex Structures 2.Challenging to fabricate
	Hybrid Metal-dielectric	0.32		
	Chiral	0.4		

Y. Gong, Z. Zhang, J. Tang, L. Ma, and K. Pang, "Research progress on terahertz achromatic broadband polarization wave plates," *Opt. Laser Technol.*, vol. 166, no. March, p. 109633, 2023, doi: 10.1016/j.optlastec.2023.109633.

Design of High contrast grating

- Initially, monolayer-silicon-based high contrast grating was developed with a subwavelength periodic dielectric-air interfaces with a period of P =100μm on top of a HRFZ-Si silicon wafer with a overall thickness of t=250μm. The grating height of a waveplate was kept at h =200μm, i.e the height of ridge from the groove and the width of ridges was kept at w.
- Modelling and the S-parameter calculations were performed for the grating using FDTD simulations.

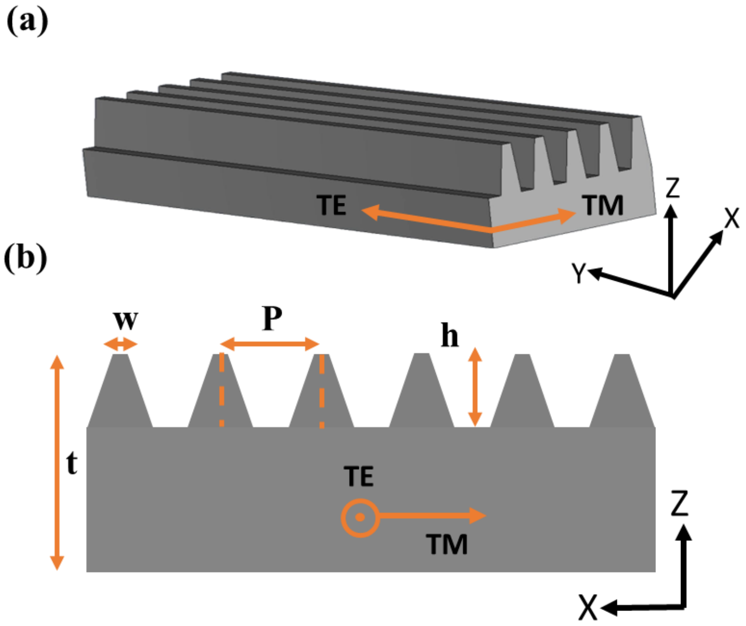

Fig.2. Schematic representation of monolayer-silicon-based high contrast grating; (a) 3D representation of a developed silicon grating (b) monolayer-silicon-based grating along XZ-axis with a design parameters.

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Characterization

- The transmission measurements were done for both the TE and TM polarizations and were compared between the FDTD Simulations, THz-TDS , THz-FDS and VNA measurements.

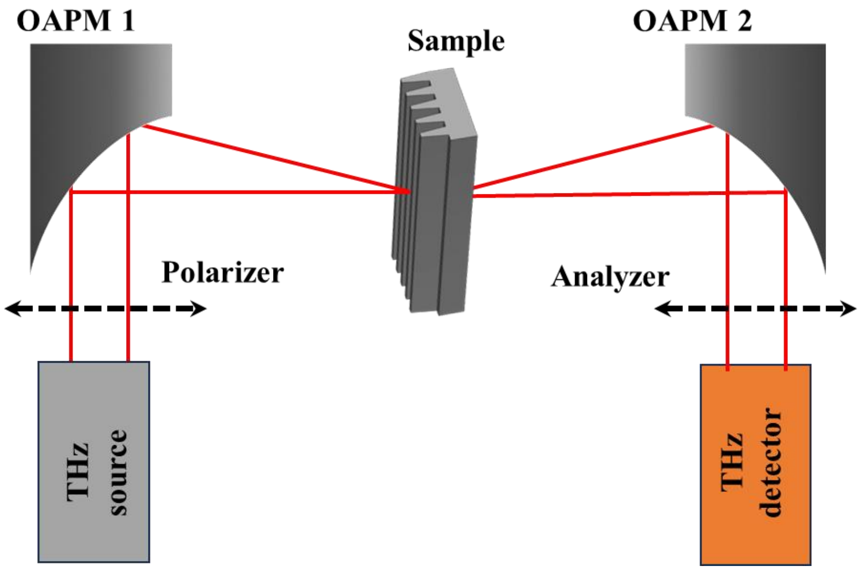

Fig.4. Experimental setup used to characterize the sample in THz TDS, FDS, and VNA systems. Polarizer and Analyzer components were used only in operation of THz TDS, FDS, and VNA systems.

THz-Setups

	THz-TDs	THz-FDs	VNA
System	TeraVil T-SPEC 800	Toptica TeraScan 750	VDI SGX
Configuration	THz source, optical mirrors, sample and THz detector	THz source, polarizer, optical mirrors, sample, analyzer and THz detector	THz source, optical mirrors, sample and THz detector
Measurement	THz pulse traces	Amplitude and phase	Amplitude and phase
Analyzing	FFT of time THz pluses yields the spectral information in the range of 0.1 – 4.0 THz	Direct spectral information of harmonic signal in frequency range of 0.1 – 1 THz	Spectral information for different WR bands (WR3.4,WR2.2,WR1.5, and WR1); needs manual stitching
Frequency Resolution	8.70 GHz	0.10 GHz	0.125 GHz

Fabrication

- Dielectric-Air Gratings were developed of high resistivity floating zone (HRFZ) silicon (Si) wafer employing the Direct Laser Ablation (DLA) technique.

- The DLA was used for fabrication of grating samples using a precisely focused laser beam to remove material from the substrate, enabling the creation of well-defined grooves and ridges.

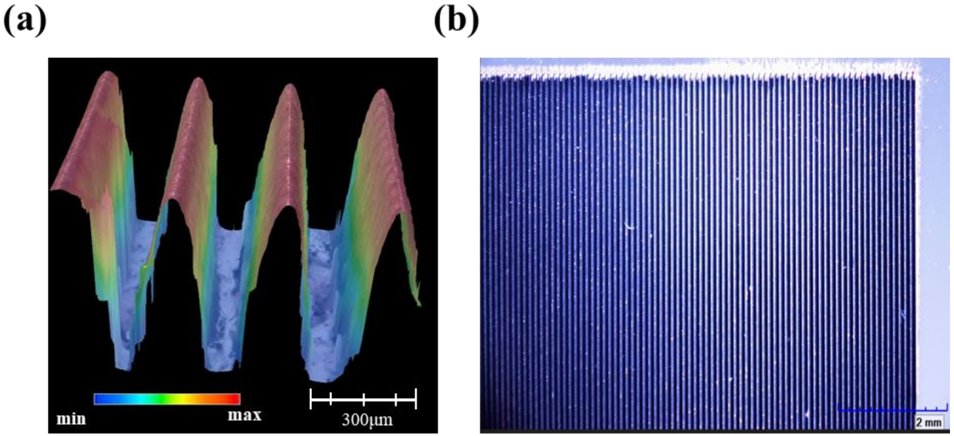

Fig.3. (a) Profile of a silicon grating was shown in colour scale along XZ-axis with a h= 200µm and period of P= 100 µm taken from the optical profilometer, showing grating ridges (red colour) and grating grooves (blue colour), (b) Microscopic image of a waveplate along XY-axis.

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- Reduction of Fabry Perot effect along TM polarization.
- Shows the phase retardation of 90 ±10 degrees between TE and TM polarizations across the frequency for a bandwidth of 200 GHz for a frequency of 0.3 to 0.5 THz and can work as a quarter waveplate (QWP).

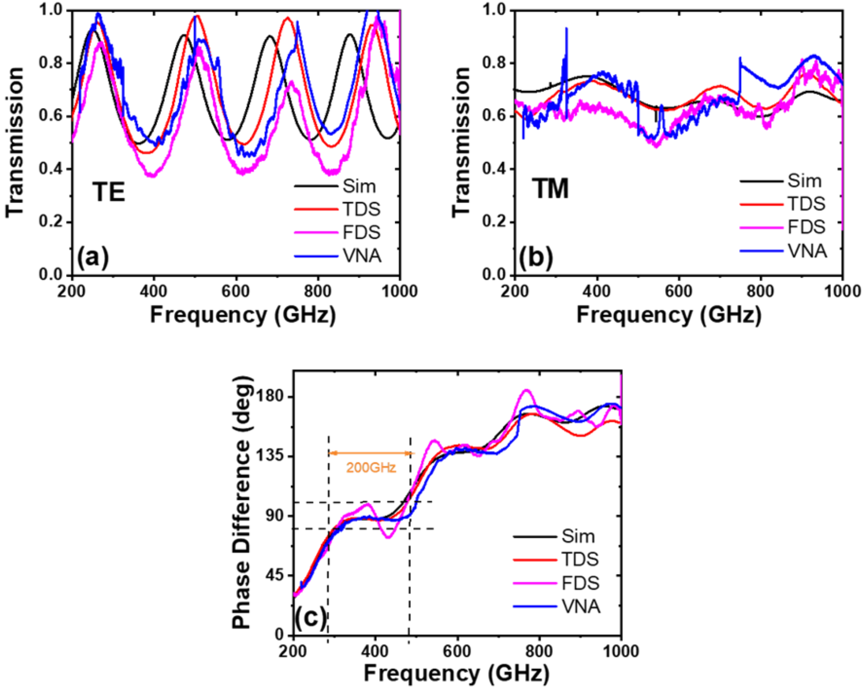

Fig.5. Transmission and Phase characteristics of a monolayer-silicon-based high contrast grating compared between FDTD simulations, THz-FDs setup, THz-TDs setup and VNA setup, (a) along TE polarization (b) along TM polarization, and (c) Phase difference between TE and TM polarizations.

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Polarization measurements:

- We conducted an experimental investigation to assess the polarization performance of a sample employing a THz Frequency Domain (THz-FDs) setup utilizing a Toptica Terascan 780 spectrometer at a specific frequency 400GHz .

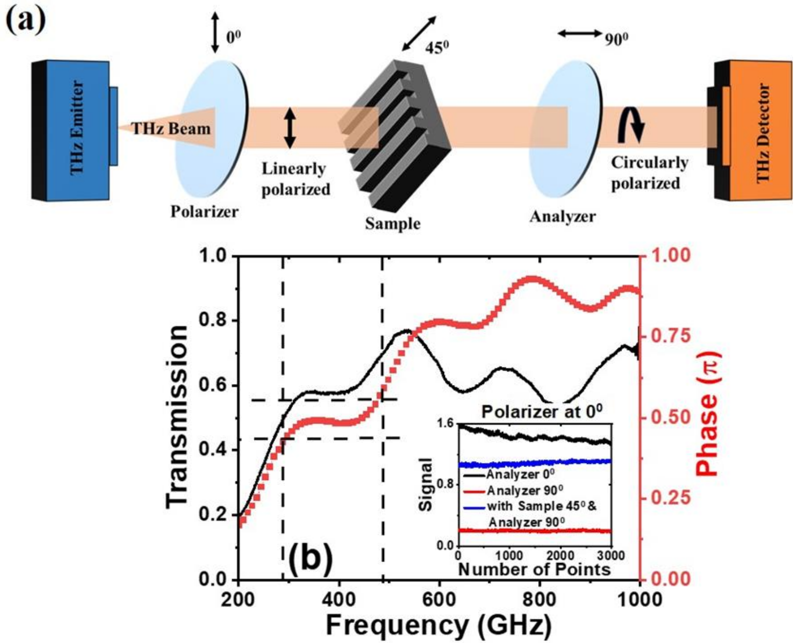

Fig.6. (a) Schematic representation of polarization measurement setup, (b) absolute transmission (left) of a waveplate measured exactly with the above shown setup configuration and the phase characteristics (right) of a waveplate normalized to π across the frequencies up to 1 THz. Inset: signal measurements in transmission mode at fixed 400 GHz frequency with both polarizer and analyzer placed parallel (black curve); with both crossed (red curve) and with the sample placed in between and oriented at 45 degrees (blue curve).

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Optimization of Waveplate

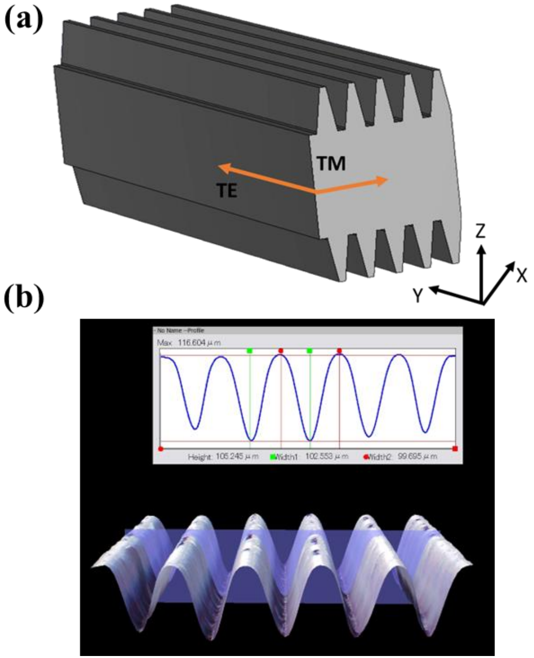

Fig.7. Schematic representation of double-sided silicon-based high contrast grating; (a) 3D representation of a developed grating (b) profile of a fabricated grating along XZ-axis.

- Period $P_T = P_B = 100\mu m$ and height of grating $h_T = h_B = 100\mu m$ on both top and bottom sides of a HRFZ-Si wafer with a overall thickness of $t = 500\mu m$.
- Improved transmission along TM polarization is observed within the frequency range of 0.4 THz to 0.9 THz approaching nearly to 100% with a broadband operational bandwidth of 500 GHz.

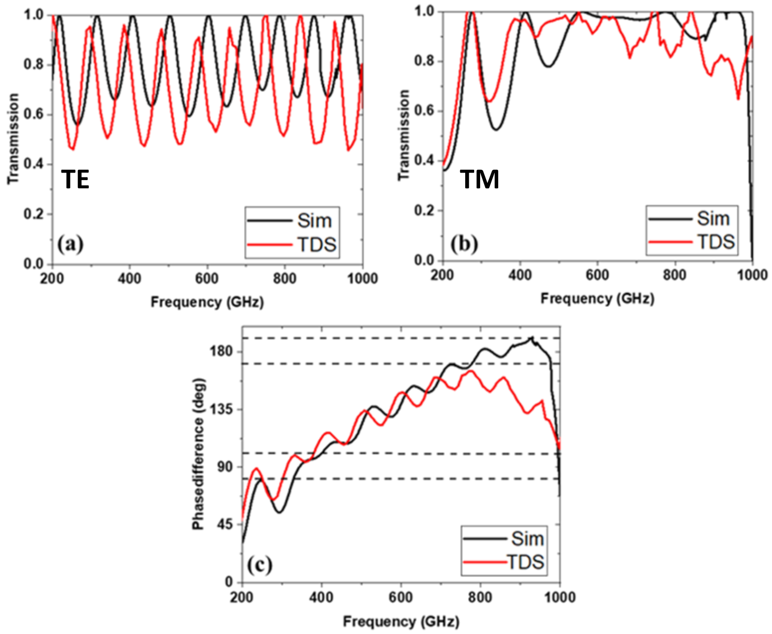

Fig.8. Double-sided dielectric-based high contrast grating (a) Transmission spectra of TE polarization, (b)TM polarization and (c) Phase retardation for simulation (Black) and measurements (Red).

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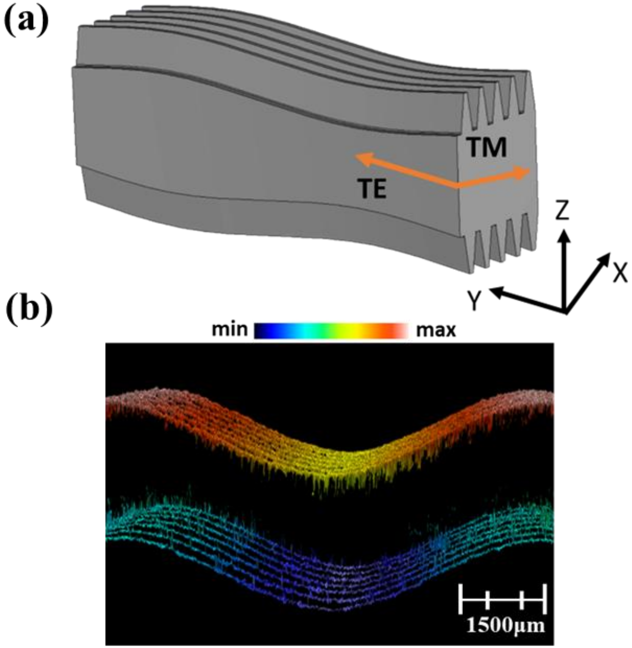
Optimization of Waveplate



- Period $P_{ST} = P_{SB} = 1500\mu m$ and amplitude $a_{ST} = a_{SB} = 10\mu m$ on both top and bottom sides of a HRFZ-Si wafer with a overall thickness of $t=500\mu m$.

- Reduced Fabry Perot effect for a broad frequency range for both TE and TM polarizations.

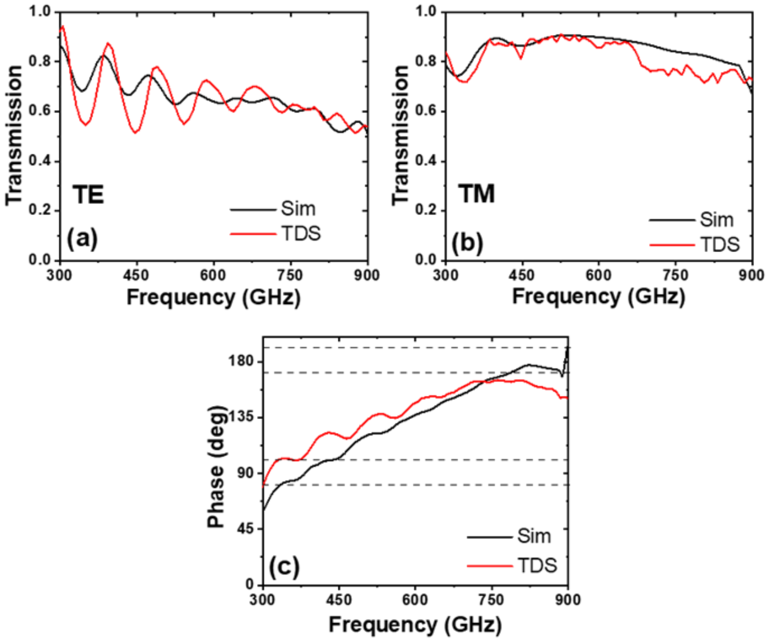


Fig.9. Schematic representation of Sinusoidal silicon-based high contrast grating; (a) 3D representation of a developed grating (b) profile of a fabricated grating along YZ-axis.

Fig.10. Sinusoidal dielectric-based high contrast grating Transmission spectra of (a) TE polarization, (b)TM polarization and (c) Phase retardation for simulation (Black) and measurements (Red).

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Conclusions

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- The high contrast grating waveplate was developed of monolayer silicon demonstrating a quarter waveplate (QWP) operation both numerically and experimentally in the frequency range of 0.3 to 0.5 THz; i.e. the operational bandwidth is 200 GHz.
- Furthermore, the transmission performance for a broadband THz frequencies is enhanced by structuring the top and bottom sides of such grating-based waveplate samples.
- Developed waveplate samples possess anti-reflective behaviour due to inclination of grating walls and sinusoidal surface modification allowing to supress the Fabry Perot effect.
- Performance of the QWP samples was validated experimentally in three different setups based on the THz-TDS, THz-FDS and VNA systems, showning a good agreement between the results.
- Such waveplates with high transmission and phase retardation offers a path toward more efficient and versatile devices in the control of phase and polarization of THz wave.

Acknowledgement

This work received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie ITN project TERAOPTICS (grant No. 956857).

A European Training Network TERAOPTICS

THz Atelier