FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

THz Waveplate based on Laser Processed Silicon Grating

Presented by: Surya Revanth Ayyagari

Supervisor: Dr. Irmantas Kasalynas

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).

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.

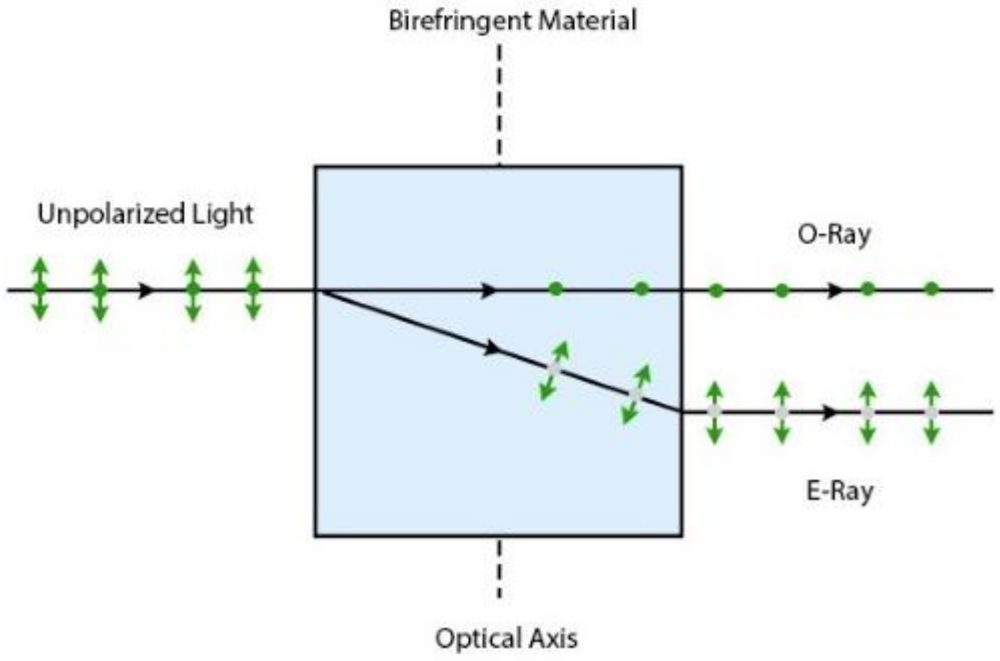

Fig.1. Scheme of Birefringence inside a birefringence material

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.

Table: Recent progress on THz waveplates

Materials classification			Bandwidth/ THz	Benefits	Drawbacks
Natural materials	Lithium niobate		~0.90	1. Large birefringence 2. Low dispersion	1. Brittle 2. High absorption 3. Complex fabrication process
	Quartz	Orthodox structure	~0.10	1. High transmittance 2. Low birefringence 3. Low dispersion	1. Low nonlinearity 2. High cost
		Special prism structure	~2.50		
	Artificial crystal		~0.20	1. Good transmittance 2. Stability 3. Low cost and easy fabrication	1. Higher refractive index 2. Weaker electrical and magnetic properties 3. High absorption rate 4. Poor thermal stability
Grating	Metal-based		~0.60	1. High phase modulation 2. High durability 3. Suitable for harsh environments	1. High absorption and reflection losses
	Dielectric-based		~0.40	2. Low loss 1. High phase modulation 2. High precision	1. More fragile than metal-based wave plates
Metamaterial	Metal-Insulator-Metal		~0.52	1. High transmission efficiency 2. Low insertion loss	1. Challenging to fabricate 2. High optical losses and absorption
	Dielectric		~0.25	1. High transmission efficiency 2. Low insertion loss 3. Good temperature stability	1. Limited bandwidth 2. Challenging to fabricate
	Hybrid Metal-Dielectric		~0.32	1. Broadband operation 2. High transmission efficiency 3. Low insertion loss.	1. Challenging to fabricate 2. High optical losses and absorption
	Chiral		~0.50	1. Broadband operation a 2. High transmission efficiency.	1. Challenging to fabricate 2. Limited polarization selectivity.

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 Silicon grating

- Initially,monolayer-silicon-based grating was developed with a subwavelength periodic material-air interfaces with a period of P =100µm on top of a HRFZ-Si silicon wafer with a overall thickness of t/2=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.

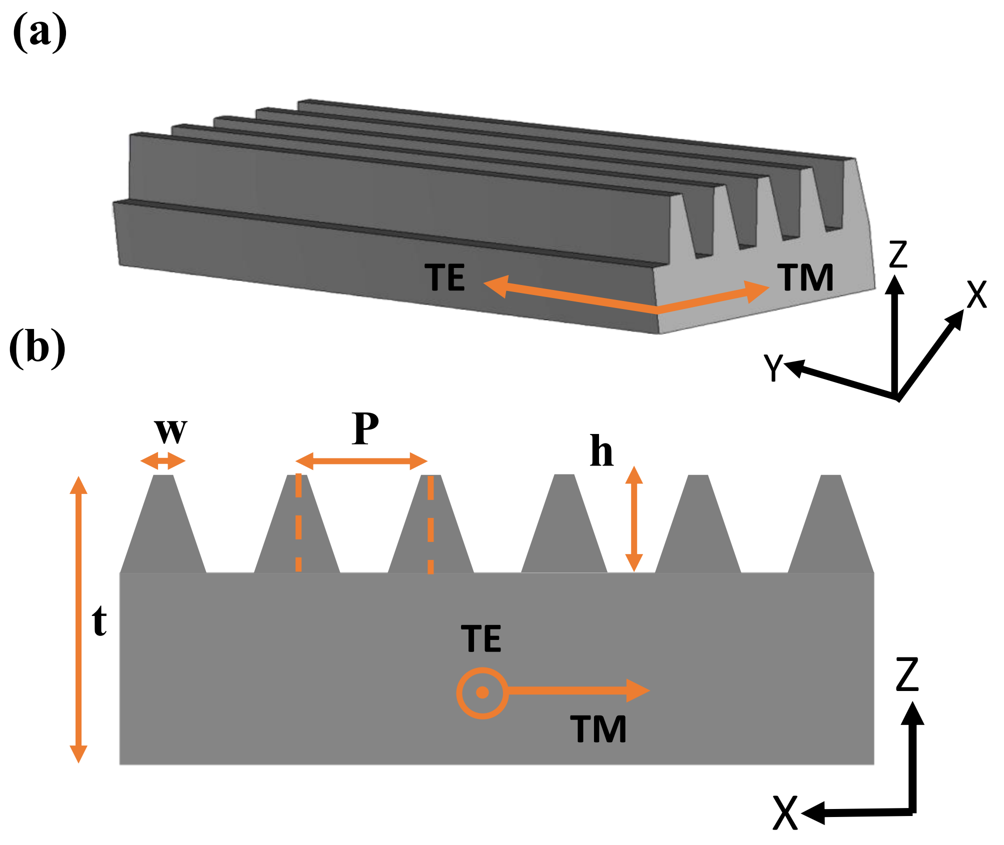

Fig.2. Schematic representation of monolayer-silicon-based grating; (a) 3D representation of a developed silicon grating (b) monolayer-silicon-based grating along XZ-axis with a design parameters.

Surya Revanth Ayyagari et al. "Wideband Waveplates Based on Dielectric Deep-Groove-Gratings in the Terahertz Range"(*undersubmission*).

Fabrication

- Material-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.

(a) (b)

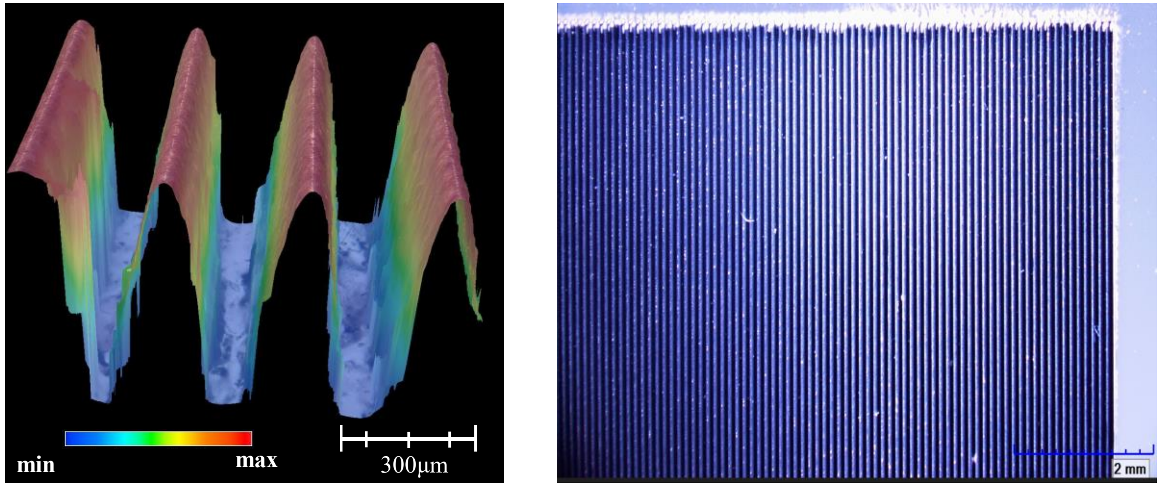

Fig.3. (a) Profile of a silicon grating was shown in colour scale along XZ-axis with a h= 200μm and period of P= 100 μm taken from the optical profilometer, showing grating ridges (red colour) and grating grooves (blue colour), (b) Microscopic image of a waveplate along XY-axis.

Surya Revanth Ayyagari et al. "Wideband Waveplates Based on Dielectric Deep-Groove-Gratings in the Terahertz Range"(*undersubmission*).

Characterization

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

- Shows the phase retardation between TE and TM polarizations across the frequency where it achieves 90 ±10 degrees of phase shift for a bandwidth of 200 GHz for a frequency of 0.3 to 0.5 THz and can work as a quarter waveplate (QWP).

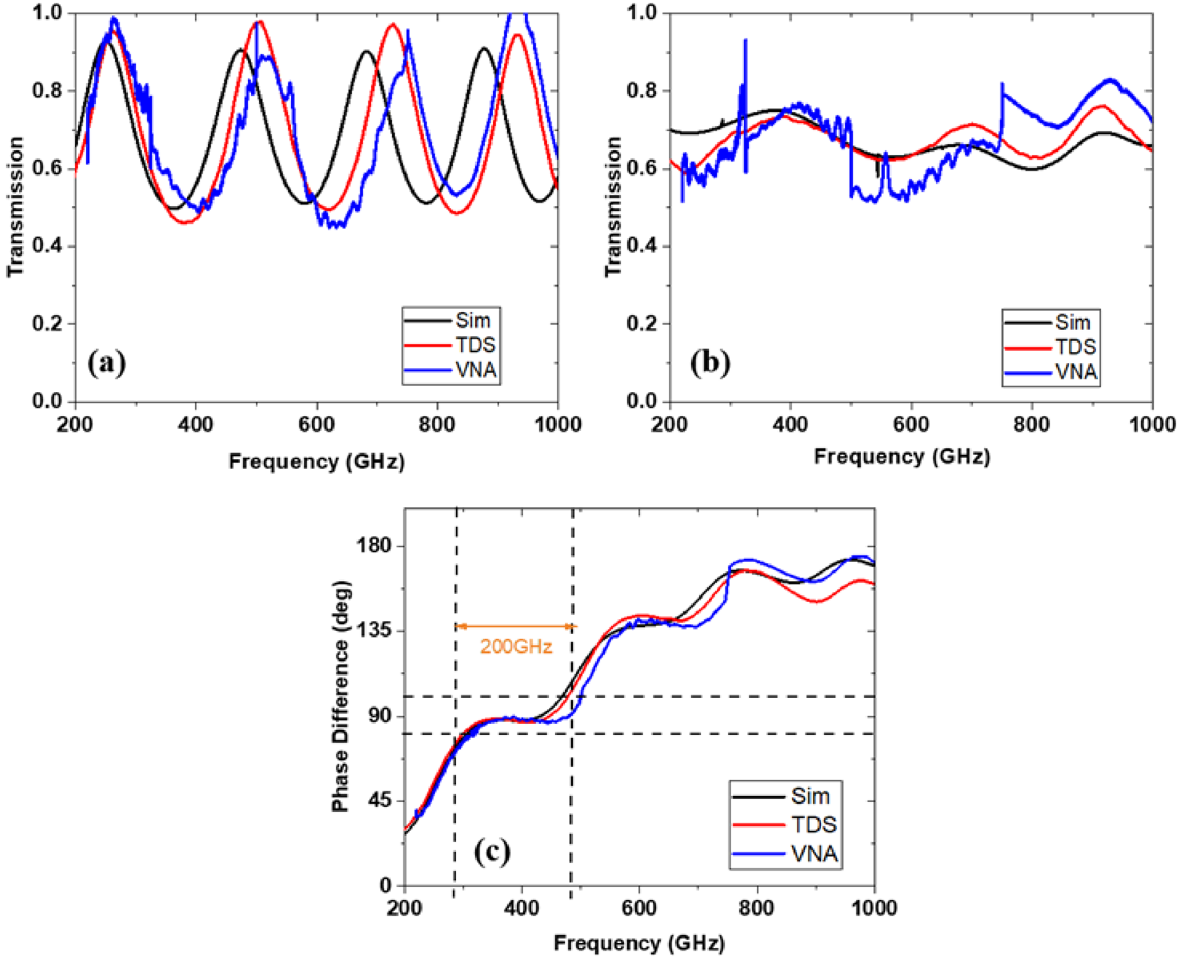

Fig.4. Transmission and Phase characteristics of a monolayer-silicon-based grating compared between FDTD simulations, THz-TDs setup and VNA setup, (a) along TE polarization (b) along TM polarization, and (c) Phase difference between TE and TM polarizations.

Surya Revanth Ayyagari et al. "Wideband Waveplates Based on Dielectric Deep-Groove-Gratings in the Terahertz Range"(*undersubmission*).

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.

(a)

(b)

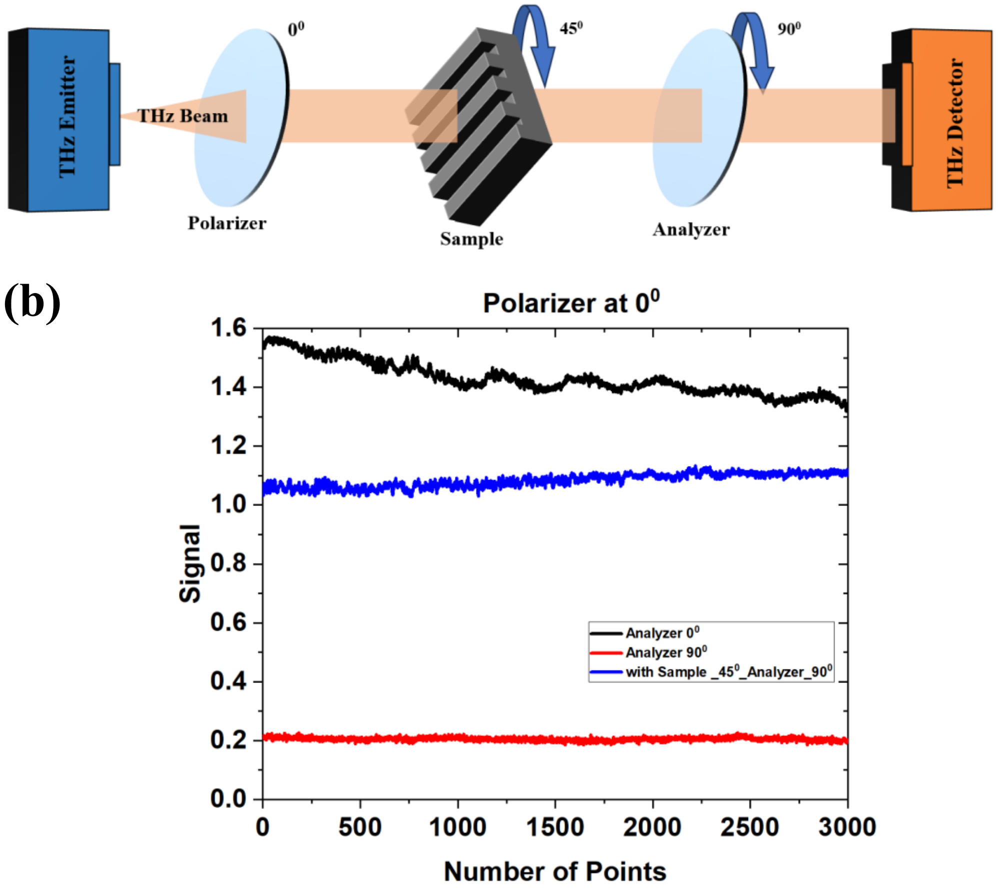

Fig.5. (a) Schematic representation of polarization measurement setup for a waveplate. (b) Measurement of different polarization states at fixed 400 GHz frequency with analyzer placed parallel (0^0) to polarizer (black curve); with both crossed (90^0) without (Red curve) and with the sample placed in between and oriented at 45 degrees (Blue curve).

Surya Revanth Ayyagari et al. "Wideband Waveplates Based on Dielectric Deep-Groove-Gratings in the Terahertz Range"(*undersubmission*).

Design of Double-sided Silicon grating

- To improve the transmission performance of a waveplate along the grating axis or TM polarization we've made a modification to the previously mentioned single-sided silicon grating waveplate transforming to double-sided silicon grating waveplate. [M. Tamosiunaite *et al., IEEE Trans. Terahertz Sci. Technol.*, doi: 10.1109/TTHZ.2018.2859619]

- 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 $t = 500\mu m$.

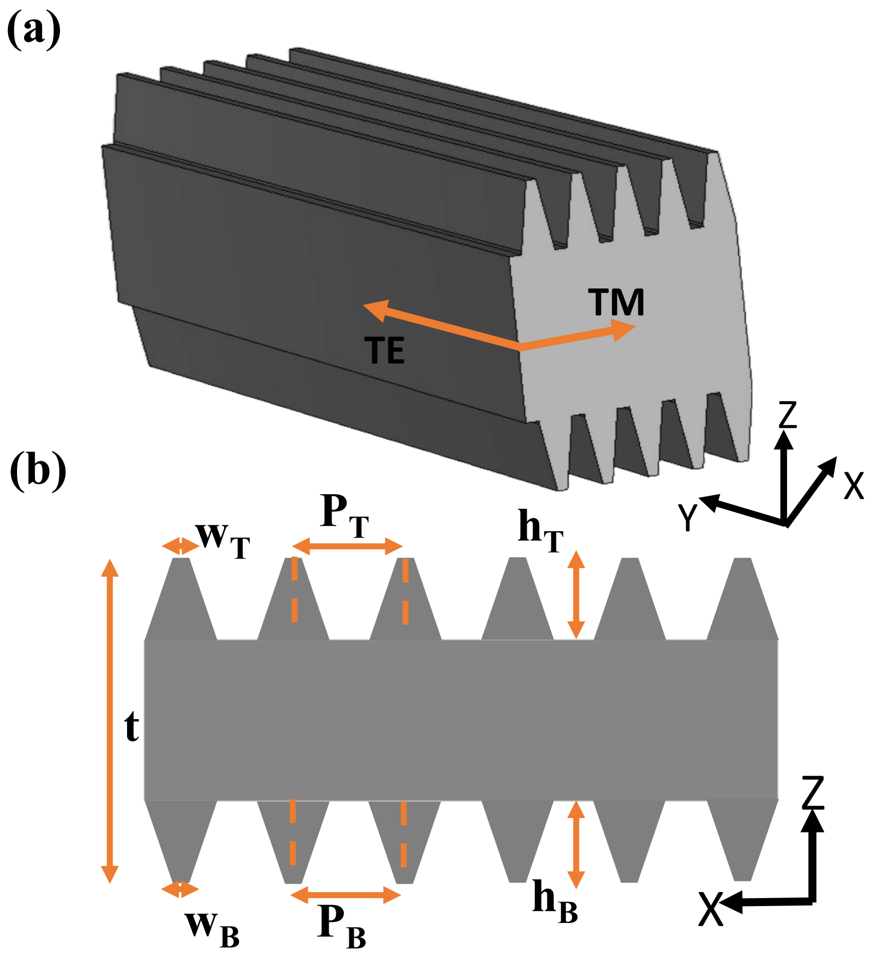

Fig.6. Schematic representation of doble-sided silicon-based grating; (a) 3D representation of a developed silicon grating (b) double sided silicon grating waveplate along XZ-axis with a design parameters.

- Enhanced transmission performance 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 for Simulation/Experimental findings for TM polarization.

- Conversely, we can achieve the required π phase shift between TE and TM polarizations, enabling the waveplate to function as a Half-Wave Plate (HWP) in the frequency range of 0.778 THz to 0.978 THz, with an operational bandwidth spanning 200 GHz for simulations.

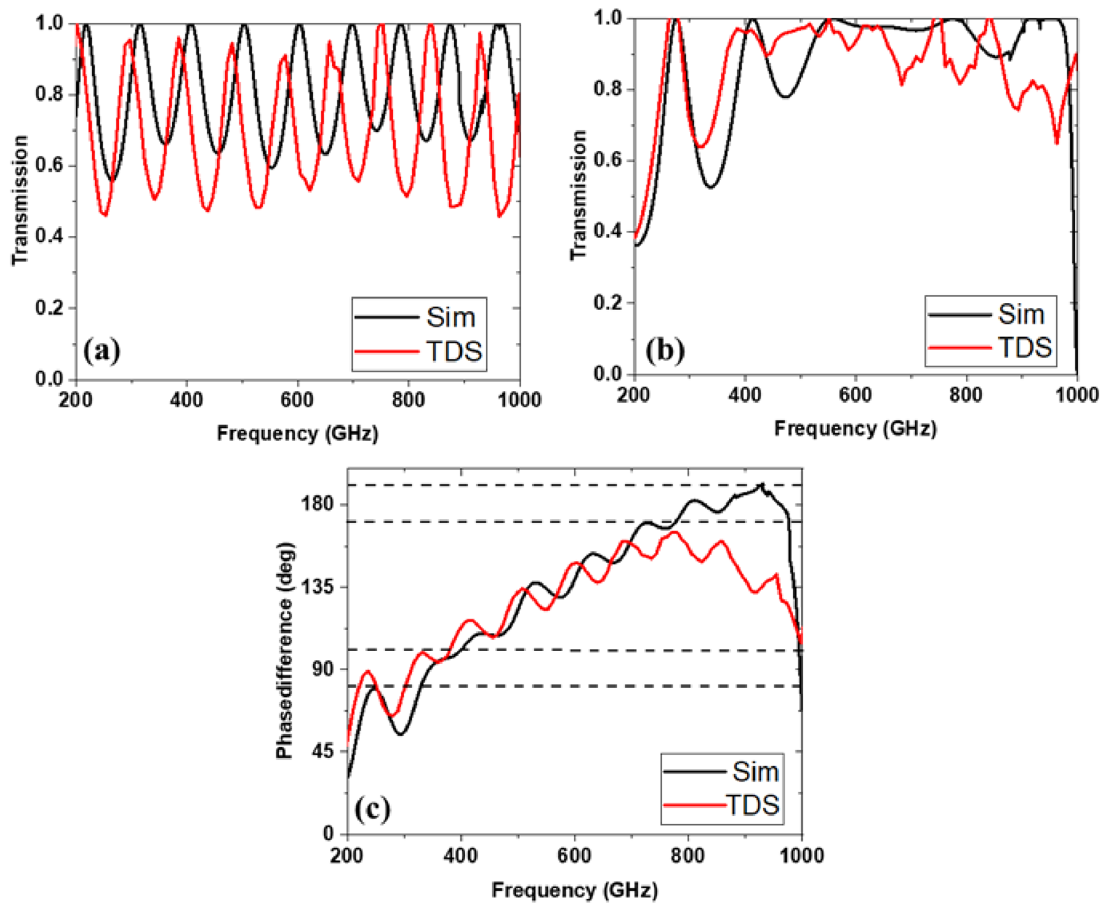

Fig.5. Double-sided dielectric-based grating waveplate (a) Transmission spectra of TM and TE polarizations for simulation (Black) and measurements (Red curve) (b) Phase measurements for simulation (Black) and measurements (Red curve).

Conclusions

- We developed a monolayer silicon grating waveplate based on artificial birefringence operating as a quarter waveplate (QWP) in the frequency range of 0.3 to 0.5 THz, with an operational bandwidth of 200 GHz is presented both theoretically and experimentally.

- Furthermore, by incorporating such similar grating structures on the bottom side of a sample helps us to improves the transmission performance of a waveplate reaching upto 100% for a broadband THz frequencies.

- The proposed waveplates possess anti-reflective behaviour along TM polarization due to inclination of grating walls allowing to supress the reflection losses caused by Silicon-air interfaces.

- Such waveplates with high transmission and phase retardation immense promise for applications requiring precise polarization control and efficient terahertz wave transmission.

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).