A Low Loss Dual-polarization Optical Diplexing Scheme for Millimeter to Terahertz Waves.

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***Abstract*—In this paper, we present an optical diplexer composed of periodic stacks of High Resistivity (HR) Silicon and Low Density Polyethylene (LDPE) disks. Operating at an angle of incidence of 30 degrees, this diplexer is characterized by a reflection band centered at 130 GHz and it acts as a band-pass transmission filter around 300 GHz. It offers a very low measured average transmission loss of 3.2% in the transmission band. Similar diplexers created using this technique will be employed with next generation ground and space-based telescopes to support simultaneous dual polarization, multiband observations.**

***Index Terms*—dichroic, diplexer, radio astronomy, submillimeter wave**

I. Introduction

THE addition of simultaneous dual polarization observation capabilities at submillimeter wavelengths offers numerous advantages. From an astronomy standpoint, simultaneous multi-band observations provide fresh insights into various astrophysical processes and it also enhances spectral line surveys. From an engineering perspective, the throughput of radio telescopes is increased and the technique of Frequency Phase Transfer (FPT)[1] is enabled. The operation of radio interferometers in the submillimeter regime is limited by atmospheric phase fluctuations, which has a particularly strong impact on Very Long Baseline Interferometry (VLBI). FPT improves sensitivity by pairing low-frequency receivers with high-frequency ones, using the strong signal-to-noise ratio of the low-frequency data to calibrate the high-frequency data. Next-generation instruments, such as the wideband Submillimeter Array (wSMA)[2], the next-generation Event Horizon Telescope (ngEHT)[3], and the Black Hole Explorer (BHEX)[4] will all require simultaneous dual polarization observation capabilities.

The key to simultaneous dual-polarization multi-band receiver operation is a low-loss multiplexing scheme, typically constructed from optical diplexers, or dichroics. These diplexers direct the telescope beam towards different receivers centered at varying frequency ranges. The performance of optical diplexers can be assessed by a number of metrics, including insertion loss, bandwidth of operation, angle of incidence, and clear aperture size. This paper presents a novel diplexer design that features simplicity, robustness, exceptionally low insertion loss, operation at high angles of incidence, wide bandwidth, and moderate beam size.

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II. Theory

The optical diplexer we have created uses a periodic stack of dielectric materials to define a transmission and a reflection band for the incoming signal beam. The equations governing the propagation of electromagnetic waves in a stack of dielectric disks are well known [5] and can be used to define a characteristic matrix for each layer of the stack. For a stack of dielectric disks, matrix multiplication of the characteristic matrix of each layer in the stack yields the equivalent characteristic matrix of the entire stack, from which the transmission and reflection of the stack can be derived. For dual polarization operation, the responses of the stack for both Transverse Electric (TE) and Transverse Magnetic (TM) waves have to be considered. At normal incidence, the two polarizations are degenerate, but as the angle of incidence increases, the two waves demonstrate increasingly different propagation characteristics. We have designed our diplexers to yield relatively similar TE and TM responses up to and including an angle of incidence of 30 degrees. Please refer to [5] for a full derivation of the equations used.

III. Design

The dielectric materials utilized in our dielectric stacks are selected based on their refractive indices and loss tangents. The thickness of the disks are chosen to effectively reflect and transmit specified frequency range. In the design discussed below, High Resistivity Silicon (HR-Si) and Low Density Polyethylene (LDPE) are used for these reasons. Specified resistivity of the HR-Si is 10 kΩ-cm, and at such resistivity level, silicon is known to be one of the lowest loss materials in the THz regime. HR-Si forms the basis of the design by defining the half-wave and full-wave transmission frequencies. The refractive index of HR-Si and LDPE are 3.42 and 1.52 respectively. The high contrast in refractive indices of the two materials is exploited to produce a strong reflection at frequencies close to quarter-wave or three quarter-wave in the HR-Si layers. In our design, we adjust the thicknesses of the two material such that the diplexer's transmission and reflection bands can be tailored to the desired frequency range.

A nine-layer dielectric stack with alternating 0.11mm HR-Si and 0.18mm LDPE layers which has a transmission band centered around 300 GHz and a reflection band centered around 220 GHz was presented elsewhere [6]. Here, we present a similar design with 0.15mm HR-Si and 0.18mm LDPE layers (Fig. 1) which behaves as a 270 GHz band pass filter in transmission, while reflecting a band around 130 GHz. Both diplexers are designed to operate with an incident angle of 30 degrees. The stack is consolidated by baking in an oven at a temperature of $\approx 110°$ Celsius with weights on top. This acts to fuse the LDPE to the HR-Si wafers and eliminate any air gaps.

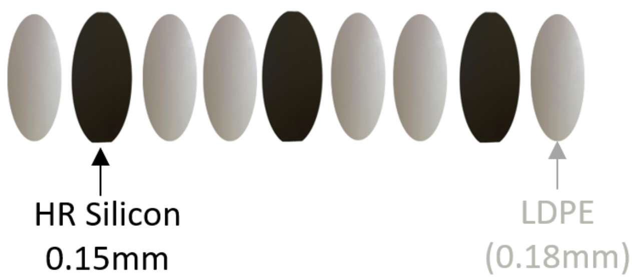

Fig. 1: The dielectric stack used to create an optical diplexer with a transmission band centered at 270 GHz and a reflection band centered at 130 GHz. The inner layers of LDPE are two stacked pieces of 0.18mm (0.36mm in total) while the outer layers are single pieces of 0.18mm. The thickness of the High Resistivity (HR) Silicon disks are 0.15mm. The clear aperture size is 100mm.

IV. Measurement Results

A. Transmission

Transmission measurements of the diplexer were performed using a Quasi-Optical Vector analyzer (QO-VNA) [7]. The diplexer was placed in a vertical holder located near the beam waist of the setup, with the holder rotated by an angle of 30° about the vertical axis of the holder. When the incoming wave is vertically polarized, the diplexer is seeing a TE incident wave; and for horizontally polarized input wave, the diplexer is looking at a TM incident wave. To switch between TE and TM measurements, we simply introduce waveguide twists to both the source and the receiver to rotate the plane of polarization by 90°. Although the QO-VNA employs a WR-3.4 source module and harmonic mixer, by working with weaker harmonics from the Amplifier-Multiplier-Chain based source, we are able to perform measurements, in a single sweep, from 195 to 370 GHz with a signal-to-noise ratio of generally better than -35 dB. Lower frequency TE transmission measurements were performed with a separate WR-6.5 VNA setup.

The results of the transmission measurements of the 130/270 GHz diplexer are plotted in Fig 2. The measured data matches the theory very well, showcasing an advantage of this type of diplexer over the more commonly employed Frequency Selective Surfaces (FSS); no complex electomagnetic simulations are required to model the stack.

B. Loss

We have performed an experimental determination of the transmission loss of the optical diplexer using an SIS receiver designed for the wideband Submillimeter Array project[2]. The method of Intersecting Lines[8], which has been proven to be able to measure optical losses accurately at short millimeter wavelengths[9], was adopted.

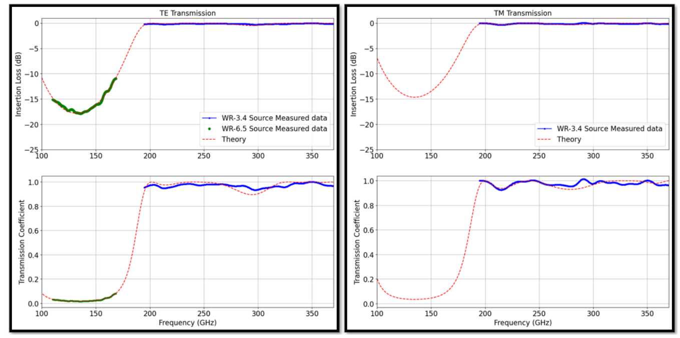

Fig. 2: Transmission curves for both Transverse Electric (TE) and Transverse Magnetic (TM) waves. The solid red curves are the predicted transmission value from our model. The measured data from both the WR-3.4 QO-VNA and WR-6.5 VNA are plotted on the same plot.

In our experiment, we placed the 130/270 GHz optical diplexer in front of the vacuum window of a 350 GHz wSMA receiver, with the diplexer inclined at an angle of 30° to the optical axis of the receiver. A series of Y-factor measurements were made with and without the diplexer. The noise temperature of the diplexer was inferred and converted to an insertion loss value, the compilation of which are included in Table I. Average loss, using two central frequencies in the passband with a bandwidth of around 1 GHz at an incident angle of 30 degrees was 3.2%.

TABLE I: Results of Transmission Loss Measurements

Center Frequency (GHz)	V-Pol Loss	H-Pol Loss
288	(3.8 ± 0.2) %	(3.4 ± 0.2) %
324	(2.5 ± 0.5) %	

V. Conclusion

We have presented an optical diplexer design, which spatially separates two bands of frequencies centered at 130 and 270 GHz, using a periodic stack of High Resistivity Silicon and Low Density Polyethylene. The simplicity, robustness, adaptability, and low insertion loss nature of this design, together with the possibility to operate at an angle of incidence of up to 30 degrees, make this class of diplexer an enabling tool for simultaneous dual-polarization multi-band receiver operation.

VI. Acknowledgements

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