Continuous variable substrate-based THz Beamsplitter
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Abstract—THz polarizing beamsplitters have been fabricated, and tested experimentally with high extinction ratios, and low insertion loss. These new beamsplitters are substrate based and manufactured from simple materials, and are consequently very affordable. The performance of these beamsplitters is enhanced using structured-surface-plasmons and bi-periodic, high “effective-fill-factor.”

I. INTRODUCTION

Beamsplitters are an important component for many THz systems, such as the Martin-Puplett interferometer, scatterometric receivers, interferometric diplexers used in heterodyne receivers, or any other system that requires partially re-routing some fraction of signal. Currently most THz beamsplitters are composed of a free-standing wire-grid polarizer, or a non-polarizing reflective substrate (such as high resistivity float-zone silicon – HRFZ-Si, or a Mylar pellicle). The problem with HRFZ-Si or Mylar is that the beamsplit ratio lacks tunability, so often times polarizing beamsplitters are preferred.

Recently we have developed new, inexpensive, high extinction ratio wire-grid polarizers that use small wire-grid period and high metal fill fraction (fill-factor – FF) [1]. These polarizers use structured-surface-plasmon (SSP) enhancement to create much higher transmission in S-orientation (wire grid axis perpendicular to the incident-radiation polarization) than expected from geometric optics, a phenomenon known as extraordinary-optical-transmission (EOT). Yet in P-orientation (wire-grid axis parallel to the incident polarization) the rejection of signal is much greater than seen in traditional wire-grids [2].

These SSP enhanced polarizers offer much higher extinction ratios than previously seen in single layer devices, but as the metal FF becomes higher the insertion loss in S-orientation tends to increase with frequency. In response to this a new bi-periodic wire-grid was created with lower S-insertion loss, but virtually the same P-insertion loss [3]. Here we analyze and report the performance of these bi-period “effective-fill-factor” (EFF) polarizers in 45° beamsplitter configuration. EFF polarizers are promising for beamsplitter use because their low S-polarized insertion loss will permit tuning the signal split ratio from 50/50 to practically 100/0.

II. EXPERIMENT AND RESULTS

The polarizing beamsplitters were fabricated with single-crystal, Z-cut quartz substrates, with 0.5 mm thickness and 50 mm diameter. The metal used was aluminum with a thickness of 200 nm. For SSP enhancement the period of the polarizer must be smaller than the incident wavelengths, so we chose 40 μm period. For this work the EFF was 75% and the EFF polarizer had its 30 μm metal strips (30/40 = 75%) split into 8 2-μm wide strips, so the actual FF was 40% (16/40 = 40%).

The perpendicular- (S) and parallel-polarized (P) transmission (with respect to the wire grid) results are shown in Fig 1(a) with the polarizer set up at both normal and 45° with respect to the incident radiation, which is TM polarized with respect to the plane-of-incidence. 45° incidence was used in this test because it is the most practical, since the transmitted and reflected beams are then orthogonal. In this configuration we see that the EFF polarizer behaves very well as a 45° beamsplitter, with transmission remaining above -3 dB for the entire measured spectrum in S-orientation. In fact, the S-transmission is superior at 45° incidence compared to normal incidence. This result is not surprising because at 45° the TM-incident radiation is approaching the Brewster angle for the quartz substrate (63° for single-crystal quartz) so has greatly reduced reflectivity at the air-quartz interface. This reduces the Q of the substrate standing waves, making the THz transmission more uniform.

The P-transmission is very low, even lower than P-transmission at normal incidence. So these polarizers offer very high extinction ratio and 50/50 split capability at some angle of orientation. The EFF beamsplitter could achieve even higher extinction ratio if a higher EFF was utilized.

To demonstrate the tuning capability of this beamsplitter we measured the transmission at 45° incidence in 10° rotation increments at 100 GHz (Fig. 1(b)), this time with TE incident polarization. Since Z-cut single crystal quartz is very transparent and substrate standing waves are minimal, reflection could then be estimated from the transmission (R = 1-T). The split percentage changes slowly and monotonically. We found that even in TE-mode, where
reflectivity should be higher (because there is no Brewster effect), a 50/50 power split was achieved ~27° away from S-orientation.

![Figure 2](image)

Fig. 2. The Mach-Zender interferometer made with EFF THz polarizers. (a) The experimental setup, measurements were taken at both output ports. (b) The measured 530 GHz signal at each port, nearly the same peak power levels were measured. The phase shift observed between output ports is created by the signal passing through the quartz substrates.

Finally, to show an example of these beamsplitters utility, we created a simple Mach-Zender interferometer operating at 530 GHz. This setup can be seen in Fig. 2(a), where the 530 GHz source is a Frequency Extension Module (FEM) from Virginia Diodes (top left corner) [4]. The 530 GHz signal is then collimated with a ZnSe lens and reflected from a mirror and into the interferometer, where the signal is collected at either output port with a Schottky diode detector. The polarization of the 530 GHz signal in this setup is again TE, with respect to the polarizer plane-of-incidence, and the 50/50 power split was still ~27° from S-polarization.

In this example the first beamsplitter (B1) was placed on a linear translation stage, so that the path ending at Port 2 could have its length varied independently. Therefore, by taking power measurements (at the output ports) as the position of B1 is varied, we can record the interference at B2. Fig. 2(b) shows the power measurements, taken at both output ports, as the position of B1 is varied. As expected, the peak power level at each port is nearly the same (there is some difference, likely caused by one of the beamsplitters being slightly off of the 50/50 ratio). The wavelength of 530 GHz signal is 566 μm, and as expected the period of the interference pattern is close to this number.

One key indicator of a working interferometer is the difference in measured power when one arm of the interferometer is blocked. Because the THz signal is split twice, the detected signal should be ¼ of the signal during constructive interference. Fig. 2(b) shows that the peak signal is ~28 mV, when either arm was blocked the measured signal was 7 mV, exactly the ¼ ratio. This was confirmed no matter which path was blocked, and at both output ports.

We have experimentally shown in this work that the EFF polarizers in [3] make excellent THz beamsplitters, with tunability from a 50/50 ratio to nearly 100/0. These polarizers have very little insertion loss, are inexpensive, and are more robust than their free-standing counterparts. This has been demonstrated by changing the rotation angle of a single polarizer and measuring the transmission of a linearly polarized signal, and by creating a working interferometer with these beamsplitters.

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