Power scaling of ultra-thin terahertz beam-splitters

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***Abstract*—A low-cost ultra-thin broadband terahertz beam-splitter based on a thin conductive layer has previously been fabricated and tested. Here, this paper shows the linearity of power scaling of the beam-splitter from lower to higher power in typical terahertz time-domain spectroscopy systems. The presented results consider multiple samples of differing thicknesses.**

I. Introduction and Motivation

Terahertz time-domain spectroscopy (THz-TDS) systems along with discrete terahertz radiation sources are continually increasing in their generated power [1], [2]. It is becoming necessary to monitor and exploit this higher generated power by sampling or splitting this generated terahertz beam. Many new optical components, such as waveguides [3]–[6], lenses [7]–[9] and filters [10] are also being produced, and beam-splitters are necessary to complete the set of optical components for THz frequencies. The beam-splitter presented in this paper can be manufactured at low-cost with an accurately adjustable splitting ratio [11]. This allows for use in scenarios where a generated terahertz beam's quality and power need to be monitored in real-time, or in high power systems, where a single source may be used to power multiple systems. This paper shows the linearity of using the presented beam-splitter in both lower (nJ) and high (μJ to mJ) power THz-TDS transmission setups.

II. Fabrication

The presented beam-splitter is fabricated using low cost materials. Common off-the-shelf generic branded household cling-wrap is used as the low-density polyethylene (LDPE) sheet stretched over a 50 mm diameter aluminum ring, forming a 6.5 μm thick substrate. This base substrate is initially weighed as a basis to determine the thickness of the applied coating. A silver conductive paint layer is then sprayed onto the surface of the substrate using an air brush at an arm's length to the substrate to ensure a uniform coating. The paint is then left to dry at room temperature for 30 minutes. The sample is then weighted again to ensure an accurate measurement of the average coating thickness down to approximately 0.1 μm. A photograph of the fabricated beam-splitters can be seen in Fig. 1.

III. Experimental Setup

Initially, low power THz-TDS experiments were performed on a Picometrix 2000XP fiber coupled THz-TDS system emitting terahertz radiation in the nJ region for characterizing the transmission of the beam-splitter at both normal and 45° incidences. High power characterization experiments were performed using with an amplified Ti:Sapphire laser pumping a $LiNbO_3$ crystal for terahertz emission in μJ region. Detection in this system was performed using a ZnTe crystal and balanced photo-diodes for electro-optical detection. Again, as with the low power system, both normal and 45° incidence transmission measurements were performed on the same beam-splitter samples. All measurements were performed in a dry atmosphere under ambient conditions.

Fig. 1. A photograph of the fabricated beam-splitters. From left to right, beam-splitters with reflection to transmission ratios of 10:90, 50:50 & 90:10 in the terahertz range can be seen. The inserts show micrographs of the surface of the beam-splitters at a magnification of 60×.

IV. Results

As can be seen in both the normal and 45° transmission plots of Figs. 2 & 3, the presented beam-splitters do not exhibit any additional spectral features measured in both low and high power THz-TDS systems. The low and high power plots show reasonable agreement considering that the high power system is bandwidth limited to approximately 1 THz, there-after the noise floor overwhelms the measured data. Minute changes in the transmission curves can be observed in all six instances, showing the performance of the beam-splitter is consistent across both low and high power systems at varying angles. The decrease in transmission of the 45° measurement follows the previously published paper [11], where the tranmission decreases as the Brewster angle of 72° is approached.

V. Potential Improvements

To increase the accuracy and consistency of fabrication of the beam-splitters, adjustments could be made in the

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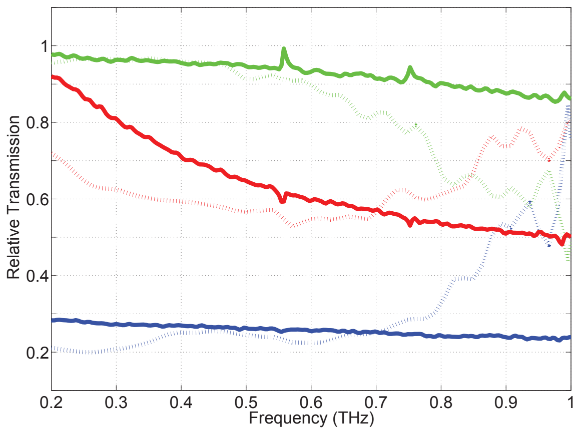

Fig. 2. The relative transmission of three samples in green, red and blue depicting samples of 90%, 50% and 20% transmission at 1 THz, respectively, for normal incidence. The solid lines denote measurements taken with a low power system, while the dotted lines denote measuremements taken with a high power system. The trend present in the plots is due to the frequency approaching roughly one fifth of the skin depth [11], [12].

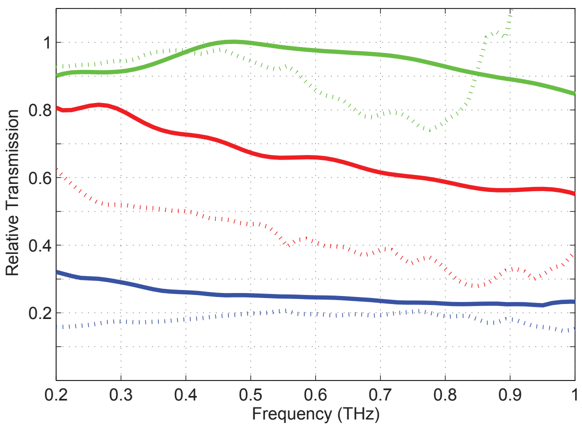

Fig. 3. 45° Angle of incidence transmission measurements of the same beam-splitters. Again, as with the normal incidence measurements seen in Fig. 2, good agreement can be seen between the plots, with no additional spectral features present between the systems. Note, the transmission amplitude deacreased compared with the normal incidence measurements, as the angle of incidence approaches the Brewster angle of the conductive paint at 72°.

fabrication process. In particular, replacing spray coating with inkject printing with its controlled droplet size and accurate drop placement could increase the uniformity of the coating, along with thickness tolerance. Moreover, machine stretching and deposition of the cling-wrap could ensure an even and flat surface, such that minimal to no lensing effect can be observed in fabricated samples.

VI. Conclusion

From the measurements, it can be seen that the presented ultra-thin conductive beam-splitter performs consistently across both low and high power systems within the terahertz range. The low-cost and ratio-adjustability of the beam-splitter provides significant advantages over the current beam-splitters in use, while the ultra-thin property enables minimal beam deflection and elminates the possibility of Fabry-Perot interference occuring in both transmitted and reflected beams, unlike with float-zone silicon, where thicker wafers exhibit significant amounts of interference and deflect the terahertz beam. The beam-splitter is also robust, with stable coatings remaining intact for well over 9 months. These properties provide the opportunity for these beam-splitters to be used in applications such as beam-sampling a terahertz Quantum-Cascade Laser (QCL), to monitor the output beam in real-time for diagnosis purposes. In addition to this, the beam-splitter provides opportunities to make use of future high power terahertz systems, where the genertated beam may be able to power multiple systems for simultaneous measurements.

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References

[1] B. Clough, J. Liu, and X.-C. Zhang, "'All air-plasma' terahertz spectroscopy," *Optics Letters*, vol. 36, no. 13, pp. 2399–2401, 2011.

[2] J. A. Fülöp, L. Pálfalvi, G. Almási, F. Krausz, S. Karsch and J. Hebling "Generation of sub-mJ terahertz pulses by optical rectification," *Optics Letters*, vol. 37, no. 4, pp. 557–559, 2012.

[3] S. Atakaramians, S. Asfar V., M. Nagel, H. K. Rasmussen, O. Bang, T. M. Munro and D. Abbott, "Direct probing of evanescent field characterization of porous fibers," *Applied Physics Letters*, vol. 98, no. 12, 121104, 2011.

[4] R. Mendis, and D. M. Mittleman, "Comparison of the lowest-order transverse-electric (TE1) and transverse-magnetic (TEM) modes of the parallel-plate waveguide for terahertz pulse applications," *Optics Express*, vol. 17, no. 17, pp. 14839–14850, 2009.

[5] K. Nielsen, H. K. Rasmussen, A. J. Adam, P. C. Planken, O. Bang, and P. U. Jepsen, "Bendable, low-loss Topas fibers for the terahertz frequency range," *Optics Express*, vol. 17, no. 10, pp. 8592–8601, 2009.

[6] B. Scherger, M. Scheller, N. Vieweg, S. T. Cundiff and M. Koch, "Paper terahertz wave plates," *Optics Express*, vol. 19, no. 25, pp. 24884–24889, 2011.

[7] Y. H. Lo, and R. Leonhardt, "Aspheric lenses for terahertz imaging," *Optics Express*, vol. 16, no. 20, pp. 15991–15998, 2008.

[8] B. Scherger, C. Jördens and M. Koch, "Variable-focus terahertz lens," *Optics Express*, vol. 19, no. 5, pp. 4528–4535, 2011.

[9] A. Siemion, A. Siemion, M. Makowski, M. Sypek, E. Hrault, F. Garet, and J.-L. Coutaz, "Off-axis metallic diffractive lens for terahertz beams," *Optics Letters*, vol. 36, no. 11, pp. 1960–1962, 2011.

[10] B. Voisiat, A. Bičiūnas, I. Kašalynas, and G. Račiukaitis, "Band-pass filters for THz spectral range fabricated by laser ablation," *Applied Physcis A: Matterials Science & Processing*, vol. 104, no. 3, pp. 953-958, 2011.

[11] B. S.-Y. Ung, C. Fumeaux, H. Lin, B. M. Fischer, B. W.-H. Ng and D. Abbott, "Low-cost ultra-thin broadband terahertz beam-splitter," *Optics Express*, vol. 20, no. 5, pp. 4968–4978, 2012.

[12] M. Walther, D. G. Cooke, C. Sherstan, M. Hajar, M. R. Freeman, and F. A. Hegmann, "Terahertz conductivity of thin gold films at the metal-insulator percolation transition," *Physical Review B.*, vol. 76, pp. 125408, 2007.