Inverse Designed THz Spectral Splitters

Sourangsu Banerji, Student Member, IEEE, Yu Shi, Student Member, IEEE, Vivian Song-En Su, Student Member, IEEE, Udayan Ghosh, Student Member, IEEE, Jacqueline Cooke, Student Member, IEEE, Yong Lin Kong, Member, IEEE, Lei Liu, Senior Member, IEEE, and Berardi Sensale-Rodriguez, Senior Member, IEEE

Abstract—This letter reports proof-of-principle demonstration of 3-D printable, low-cost, and compact terahertz (THz) spectral splitters based on diffractive optical elements (DOEs) designed to disperse incident collimated broadband THz radiation (0.5–0.7 THz) at a prespecified distance. Via inverse design, we show that it is possible to design a diffractive optic that can split broadband incident spectrum in any desired fashion, as is evidenced from both finite-difference time domain (FDTD) simulations and measured intensity profiles using a 500–750-GHz vector network analyzer (VNA). Due to its straightforward as well as simple construction without the usage of movable parts, our approach, in principle, can have various applications such as in portable, low-cost spectroscopy as well as in wireless THz communication systems as a THz demultiplexer.

Index Terms—Diffractive optics, inverse design, spectral splitter.

I. INTRODUCTION

SPECTROMETERS are widely used in optical characterization, chemical analysis, etc. [1], [2]. Traditional spectrometers harness gratings (typically one for each blazing wavelength or multiopters) or prisms, coupled with other mechanical and electronic parts, to disperse and detect the incident spectrum [1]. The necessity to assemble multiple components within a single system renders them bulky, sensitive to alignment, and suffering from low throughput due to crosstalk. Hence, they are not the optimal choices for broad commercial and industrial applications, where small footprint and simple hardware are required [2]. From such a perspective, coded apertures have been previously developed to construct compact computational spectrometers over both visible [3], [4] and infrared [5] regimes. However, such an approach is limited to narrow spectral bands and sensitive to noise.

Nonetheless, from a computational perspective, we can show that a single broadband diffractive optic can be inverse designed via numerical optimization of the structure’s surface.

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Sourangsu Banerji, Jacqueline Cooke, and Berardi Sensale-Rodriguez are with the Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT 84108 USA (e-mail: sourangsu.banerji@utah.edu).

Yu Shi and Lei Liu are with the Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556 USA.

Vivian Song-En Su, Udayan Ghosh, and Yong Lin Kong are with the Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84108 USA.

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Fig. 1. (a) Schematic of the spectral splitter with a splitting distance \(d = 35\) and 50 cm under broadband illumination \(\lambda_1 = 0.6\) mm [0.5 THz], \(\lambda_2 = 0.5\) mm [0.6 THz], and \(\lambda_3 = 0.4\) mm [0.7 THz]). The designed structure splits the incoming THz wave into a series of spatially separated lines at the prespecified design distance. (b)–(e) Pixel height distribution for the spectral splitter with a maximum pixel height of 2 mm. The dimensions (length and width) of the spectral splitter were 40 mm. (f) Optical micrograph of a fabricated sample.
is based on a gradient descent assisted binary search, have been provided in our earlier works [12], [13], [16], and [17]. Regardless of the particular algorithm employed for optimization, the two key metrics that guide the inverse design are (1) choice of an appropriate target function during the initiation of the optimization algorithm and (2) suitable Figure of Merit (FoM) function to enable a convergent solution. In this work, the target function \( T_i \) was defined as a Gaussian function with full-width-at-half-maximum (FWHM), and \( Wi \) determined by the far-field diffraction limit. That is

\[
T_i(x') = \exp \left\{ - \frac{(x' - x_{fq,i})^2}{(2 * W_i)^2} \right\}
\]

where \( x' \) denotes spatial position and \( x_{fq,i} \) denotes the spatial location at which intensity peaks in the observation plane for each frequency sample. The FoM was defined as

\[
\text{FoM} = \frac{\sum_{i=1}^{N} \omega_i \theta_i}{N} - 10 \sum_{i=1}^{N} \omega_i \phi_i
\]

where the first and the second terms in (2) describe the average weighted efficiency \( \theta_i \) and the the weighted normalized absolute difference \( \phi_i \) over \( N \) wavelength samples is written as

\[
\theta_i = \frac{\int_{x_{min}}^{x_{max}} I_i(x') T_i(x') dx'}{\int_{x_{min}}^{x_{max}} I_i(x') dx'}
\]

\[
\phi_i = \frac{\int_{x_{min}}^{x_{max}} \text{Norm}(I_i(x')) - T_i(x') dx'}{\int_{x_{min}}^{x_{max}} dx'}
\]

The term \( I_i(x') \) denotes the simulated intensity distribution function and \( T_i(x') \) is the designated target function for the \( i \)th frequency sample. \( x_{min} \) and \( x_{max} \) are the limits of integration spanning from the leftmost to the rightmost in these structures. \( \omega_i \) denotes the weighting coefficient which was fixed at 0.99 in the designed structures. The optimization and simulation of the structures were done using custom-made MATLAB code and Lumerical finite-difference time domain (FDTD) solutions, respectively.

The dimensions of the splitter were taken to be 40 mm by 40 mm in length and width, respectively. The structure consisted of multilevel pixels having maximum thickness \( h_{max} = 2000 \, \mu m \), minimum thickness \( h_{min} = 200 \, \mu m \), and height level step \( \Delta h = 200 \, \mu m \); which sets the number of distinct height levels \( P \) to \( P = 10 \). The pixels have a width \( w = 400 \, \mu m \); which sets the number of pixels, i.e., \( N = 200 \). The THz spectral splitters were designed to split the incident broadband radiation at a distance \( d = [35 \text{ and } 50 \text{ mm}] \). In total, four different spectral splitters were designed to portray the robust and dynamic splitting capability of our inverse designed-based formulation. Fig. 1(b)–(e) depicts the pixel height profile along with relevant geometric dimensions for all the designs.

Polylactic acid (PLA) was taken as the design material for the splitters. Refractive index and extinction coefficient were taken based on the values measured in our previous work [18]. Other materials like polystyrene have an overall lower absorption in this frequency range [19] but are not 3-D printable at our current facilities.

### Results and Discussion

Figs. 3(a) and (b) and 4(a) and (b), respectively, depict the simulated and measured spectral maps of two spectral splitters that were designed to split incident THz frequencies in a regular sequence (gradual split) across the observation plane at a predetermined distance of 35 and 50 cm for the designed frequencies of 0.5, 0.6, and 0.7 THz. In addition to this, Figs. 3(c) and (d) and 4(c) and (d) portray the simulated and measured spectral maps of a separate set of two more spectral splitter designs that were designed to split the
For regular-sequence spectral splitter designs, the spatial–

regular spectral split due to the spectral correlation function.

directories, the correlation function for random
designs becomes narrower, which makes it easier to distin-
guish between frequencies. These observations are consist-
tent with those of earlier works reported in the literature
for such diffractive optic-based splitter designed at optical

frequencies [20]–[22].

However, here an important observation can be made. The
splitter designs, which had a random non-monotonic split of
the incident THz frequencies, depicted relatively better per-
formance than their regular-sequence counterparts. In general,
samples 2 and 4 have a clean spectral map with suppressed
side lobes with respect to both sample 1 and sample 3. In fact,
one can observe that sample 2 has the best split performance
among all the four designs.

In addition to the spectral map, the amplitude of the THz
beam and, hence, the loss performance of the splitter were
analyzed. The raw data showed that the amplitudes of the
diffractive beams vary in different measurements, but the loss
of the proposed splitter, which is mainly from the dielectric
loss of the material with a complex refractive index, was
estimated to be around 12 dB in all cases. Although this loss
is relatively larger than that reported in some other works,
e.g., [23], [24], our results demonstrate the effectiveness of the
proposed design principle with a freeform fabrication approach
using 3-D printing. In the future, the loss can be lowered by
employing materials with lower absorption (e.g., polystyrene).

Finally, the appearance of substantial side lobes in the
measured results can be attributed to two reasons: (1) imper-
fection in fabrication due to the inherent limitation of 3-D
printing (resolution $\sim 20 \mu m$ in $[z]$ and $\sim 400 \mu m$ in $[x, y]$)
and (2) imperfection in the measurement setup. A theoretical
statistical study was already conducted on a very similar
structure, i.e., a multilevel diffractive lens in [17] to showcase
how the performance of the multilevel structure degrades with
the inherent imperfection of fabrication, i.e., error in height
and width of each pixel as well as density variations leading
to index nonuniformities; and hence, a detailed discussion is
omitted here. From the measurement perspective, the receiver
VNA extender was manually moved along the desired plane,
which will introduce additional misalignment errors. Besides,
the receiver WR1.5 horn antenna is not a perfect point detector.

Instead, its radiation pattern is also a Gaussian beam with cer-
tain beamwidth and substantial side lobes, which may broaden
the main lobe and introduce side lobes in the measurements.

IV. CONCLUSION

In conclusion, we have demonstrated compact THz spectral
splitters via inverse design which is capable of splitting
incident broadband THz waves in free space with appreciable
accuracy. Barring the challenges associated with the current
state-of-the-art 3-D printing technology and the usage of better
measurement facilities, this simple straightforward proof-of-
concept demonstration of such spectral splitters evidences the
fact that the proposed structures can be crucial in enabling
portable, low-cost spectrometers as well as in wireless com-

munications as THz demultiplexers.
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