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2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). https://doi.org/10.1109/IRMMW-THz.2018.8509901

Persistent identifier of this version: https://doi.org/10.25926/q34c-6h58

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***Abstract*—An array of terahertz sources in 0.13 µm SiGe BiCMOS has previously been developed to mitigate the well-known issue of low available power from compact terahertz sources. However, the device projects beams toward different, non-overlapping directions, rendering it unsuitable for use as a general-purpose illumination source. To address this issue, custom optics are employed for incoherent power combining, and subsequently utilized in a demonstration of terahertz imaging.**

I. INTRODUCTION

LOW-cost sources of terahertz waves are a requirement for the widespread adoption of terahertz technologies. Integrated circuit-based solutions are desirable to this end, as they are convenient to operate and amenable to mass-production. However, the achievable terahertz power of electronics is limited due to the cutoff frequency of transistors. One way of approaching this problem indirectly is to make use of multiple, independent sources that generate power in parallel. This strategy has been employed to realize a sixteen-element source array that radiates 1 mW overall at 530 GHz through a hyper-hemispherical lens [1]. However, the lens projects the radiation from each source into a unique direction. This diminishes the device's suitability for imaging applications, as illustrated in Fig. 1(a); a conventional optical system focuses the individual finite-width beams, producing dead-zones. Thus, mechanical scanning is required in order to sample the entire object, which is highly undesirable. In this work, we devise custom optics that cause all beams of the source array to overlap, which is a form of incoherent power combining toward low-cost terahertz-range imaging systems.

II. EXPERIMENT AND RESULTS

The optics that we have employed to combine the beams are shown in Fig. 1(b), labelled "Lens A" and "Lens B." They are manufactured from HDPE plastic ($n = 1.5$, $\alpha = 0.25$ cm^{-1}) with computer-numerical controlled lathing. Lens A is an aspheric biconvex optic placed a $2F$-distance from the source array. This lens collects the beams and causes them to converge towards a point on the opposite side, at an equal distance from the lens. Thereafter, a similarly aspheric plano-concave optic (Lens B) intercepts these beams before they reach this point. The focal point of the second optic coincides with the back-side $2F$-point on the right. Thus, the plano-convex optic redirects the central rays of the beams before they converge, such that they exit parallel. Parallel rays are also achieved in the simpler setup in Fig. 1(a), but the beams in Fig. 1(b) are not focused by this operation; they are divergent, and hence they overlap. It is noted that the sources are un-correlated, free-running oscillators, and hence this overlap is a form of incoherent power-combining.

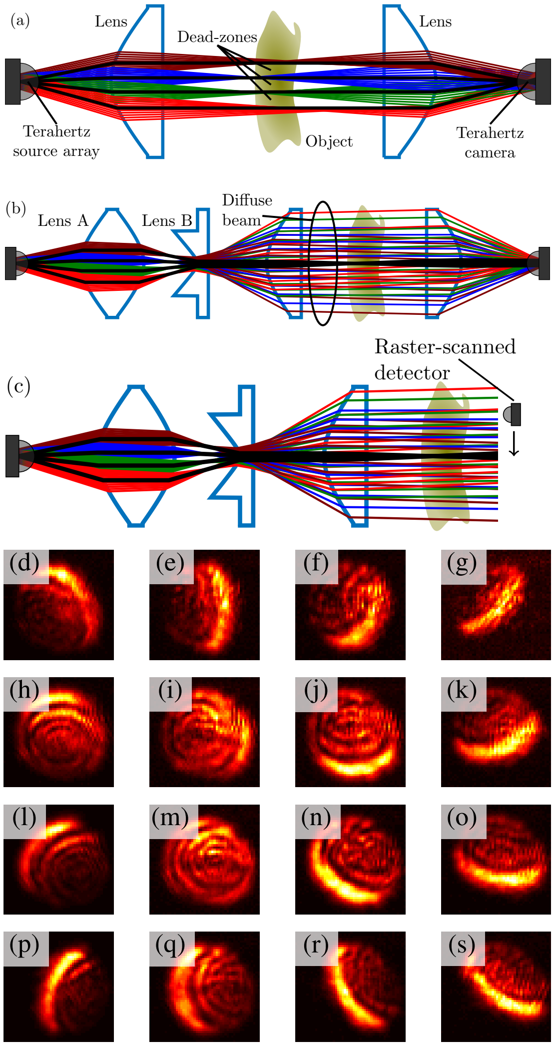

Fig. 1. Diffuse illumination, showing (a) how the use of a conventional optic with the source array produces dead-zones, where beams from distinct sources are identified with different colors and central rays are shown in black, (b) a two-lens solution to the dead-zone issue, (c) the imaging setup employed in this work, and (d)–(a) no-object scans of individual sources, in normalized linear scale, where all images span 5×5 cm^2.

Following the power-combining optical system, a plano-convex lens is employed to pass the beams through a given object. Thereafter, our ultimate aim is to use a second plano-convex lens to make the beam impinge upon a solid-state

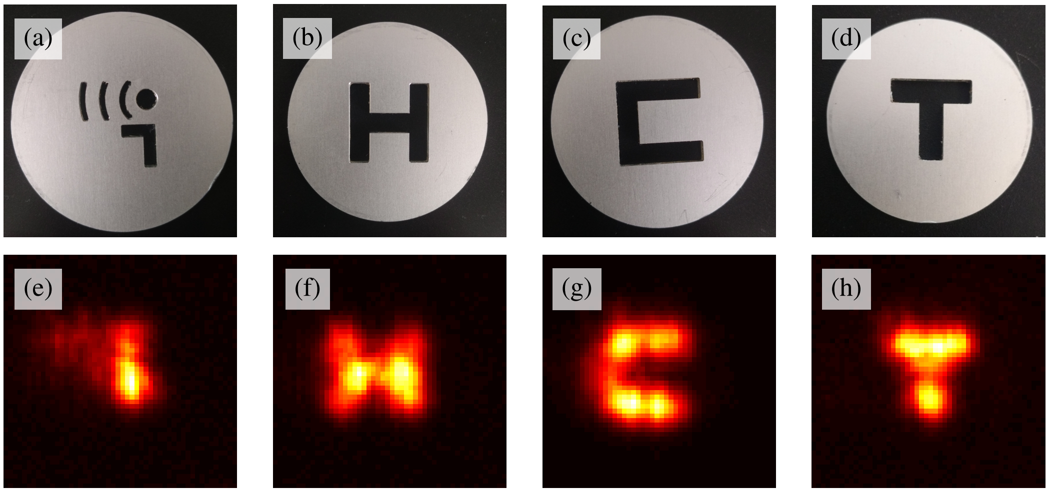

Fig. 2. Imaging demonstration that makes use of the aggregate, sixteen-source terahertz beam, showing (a)–(d) objects to be imaged, and (e)–(g) results of imaging procedure, in normalized linear scale, where all images span 5×5 cm^2.

terahertz camera, such as the 1 k-pixel CMOS-based camera that has previously been reported [2]. This would result in a terahertz imaging system that makes use of inexpensive integrated circuits for both terahertz generation and detection, and has no need fof mechanical scanning. However, the aforementioned terahertz camera operates from 0.7 to 1.1 THz, and hence it is unsuitable for use with the 0.53 THz source array. For his reason, we make use of a raster-scanned single-pixel SiGe HBT detector in the present work, as shown in Fig. 1(c). Although this is contrary to the ultimate aim of an imaging system that is free from the necessity of mechanical scanning, it is sufficient to demonstrate that the optical power-combining system functions as intended.

In order to determine whether the beams are successfully overlapped, a no-object raster scan is taken for each of the sixteen sources in the source array, and the results of these scans are given in Fig. 1(d)–(s). This gives a cross-sectional view of the beam shape that is output from the first plano-convex lens. It can be seen that, whilst the beams are not identical, they have successfully been made to overlap, and hence the aggregate beam that results from switching multiple individual sources on must incoherently combine the power from these sources. Thus, the functionality of the custom optical system that is the main subject of this work is successfully validated.

An imaging demonstration is performed that makes use of an aggregate beam with all of the sources switched on, using the experimental setup shown in Fig. 1(c). Photographs of all of the objects that are employed for this purpose are included in Fig. 2(a)–(d). These objects block the majority of the beam, allowing a small amount of it to pass. The resulting terahertz images are given in Figs. 2(e)–(g). It can be seen that the corresponding letters are clearly recognizable in the terahertz beam profile. That said, the images are not especially sharp, and finer details such as those in the object that is shown in Fig. 2(a) are entirely blurred. This is ascribed to the limited resolution of the terahertz detector. Additionally, diffraction may play a role in the degradation of overall image quality.

The efficiency of the optical system is evaluated using the Thomas Keating terahertz power meter that was previously employed to determine the output power of the source array [1]. For this procedure, the power meter is first illuminated with the source array in isolation, and subsequently with the output of Lens B. For both experiments, all sources in the terahertz source array are switched on, and the measured efficiency is 40–45%. This is consistent with expectation, as the dielectric absorption through the thickest path (i.e. along the optical axis) is ∼60%. This loss can likely be reduced in subsequent designs, either by optimisation of the optical system, or by use of lower-loss dielectrics.

III. CONCLUSION

We have employed custom optics to combine the radiated power of several sources in a SiGe BiCMOS-based terahertz source array into a single illumination source, for a successful demonstration of terahertz imaging. Such low-cost sources of terahertz power hold potential to accelerate terahertz waves towards practical applications.

ACKNOWLEDGEMENT

This was supported by DFG, under the TEASAR project.

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