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Incoherent Power Combining of THz Source Arrays

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***Abstract*—In this paper, we investigate the multi-chip scaling of a previously developed incoherent 4x4-pixel 0.53-THz 1-mW source array, implemented in a 0.13-µm SiGe BiCMOS technology. A standalone module under-samples the illumination space due to a large pixel pitch given by the implemented triple-push oscillator topology coupled with narrow pixel beams. Therefore, we present the concept of super-array configurations by arranging multiple source arrays, achieving an increased fill factor, increased radiated power, and wider illumination aperture. Moreover, such super-array configurations can help to reduce the influence of spurious reflections at THz frequencies by providing a diffused radiation. For a 2x1 super-array, the 10-dB fill factor increased from 10.9 to 61.8% while maintaining the illumination aperture; and the net radiated power doubled to 2 mW (3 dBm). For a 2x2 super-array, the illumination aperture quadrupled; the radiated power and the 10-dB fill factor at 0.53 THz were 4 mW (6 dBm) and 46.1%, respectively.**

I. INTRODUCTION

RECENTLY, terahertz (THz) source arrays have attracted attention to compensate for the lack of high power radiation sources in the 0.3 to 3 THz band. In a source array, incorporating several sources into a single silicon chip increases the radiation power. Different source elements can either be locked in-phase to emit a coherent radiation, or they can be unlocked and oscillate freely. Both phase-locked and free-running source arrays have previously been presented. Note that due to the costs and fabrication complexities associated with space limitations on the number of sources that can be implemented in a single chip, multi-chip super-arrays offer an efficient path to increase the radiation power further. However, if this technique is attempted with phase-locked sources, then the coherent nature of the radiation can lead to strong undesired interference effects [1]. On the other hand, a super-array composed of unlocked source array modules can be scaled indefinitely, in principle. Such devices are also less prone to specular reflections due to weak spatial coherence.

The device under investigation here is designed for high directivity by packaging the silicon chip together with a hyper-hemispherical silicon lens [1]. In this way, each beam radiates individually in a unique direction. This fact leads to spatial under-sampling at the illumination aperture. Note that silicon lenses are further required for improving the front-to-back ratio, suppressing substrate modes, and it acts as a heat sink. As previously discussed in [2], a larger fill factor (FF) is desired for addressing non-scanning or single-shot THz imaging with such devices. External optics can be designed to overlap the individual beams, thereby mitigating these dead-zones, but output power suffers due to attenuation and Fresnel losses [2]. Although this approach improves the fill factor of a single source module, it becomes impractical for employing multiple chips simultaneously. Therefore, in this work, we present a novel approach for incoherent power combining of multiple THz source arrays by arranging them in a super-array configuration. Increased efficiency and scalability are significant benefits over the external-optics solution.

II. EXPERIMENTS AND RESULTS

Two different supper-array configurations were investigated experimentally: the beam pattern profile characterizations of a 2x1 and a 2x2 arrangement are presented in Sec. II-A and Sec. II-B, respectively. Both the beam pattern profiles have been characterized with a CMOS THz camera from Ticwave GmbH, Germany, which is based on the FPA-chip presented in [3]. The camera module was operated at 30 fps by averaging over 1024 frames for reaching a high SNR [4], and it has been mounted onto a U5R robot arm. Moreover, it was operated in power metering mode, i.e., it was used as a single pixel detector by integrating over all the pixels as in [4]. Note that the individual source array modules are packaged in a 3x3x5 cm^3 large metal housing resulting in a minimum center-to-center distance between two devices of 5 cm.

A. 2x1 Super-Array

In this arrangement, two source arrays were placed at a 5-cm center-to-center distance and rotated by 6.25 degrees towards each other. For this characterization, a goniometric scan of the overall radiated power magnitude was performed with the THz camera, centered upon a point that was equidistant between the two devices. The measurement results have been verified through a ray-tracing simulation. To assess the increase in beam overlap, we introduce a 10-dB FF, which determines the percentage share of the radiated power with an SNR $\geq$ 10 dB within a rectangular sub-area where a signal is detected.

Fig. 1 demonstrates that measurement and ray-tracing simulation results match at a 15-cm distance, where the 10-dB FF is increased from 10.9% for a single source module to 61.8%. A comparison between the total integrated power for the combination of two source arrays and the sum of both single ones (SA1 and SA2) verifies a doubled radiated power at 0.53 THz to 2 mW (3 dBm).

B. 2x2 Super-Array

In a subsequent experiment, four source arrays (SA1 to SA4) were placed in a rhombus arrangement, as indicated

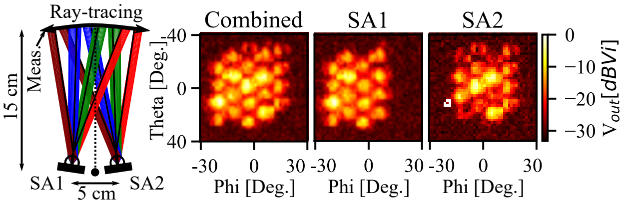

Figure 1. Ray-tracing simulation and goniometric scan measurement results of the 2x1 super-array configuration performed at a 15-cm distance for the combined beam and the single beams. All the beam pattern profiles are normalized to the maximum of the combined beam and plotted in a logarithmic scale. The 10-dB FF is 61.8% while maintaining the illumination aperture, and the radiated power at 0.53 THz is 2 mW (3 dBm).

in the ray-tracing simulation plot in Fig 2, to simultaneously increase the illumination aperture, the radiated power, and the fill factor. SA3 and SA4 were shifted by 90 degrees towards SA1 and SA2 to realize a minimum center-to-center distance of 5 cm. This arrangement caused the former two devices to radiate in co- and the latter two devices to radiate in cross-polarisation. In addition to the arrangement optimization, the rotation of two devices is an example of polarisation diversity, which can be beneficial for some applications. The versatile device arrangements were chosen to analyze how the above-mentioned performance metrics scale in such a multi-chip THz illumination system. Because the THz camera has been mounted onto a U5R robot arm with limited mobility, a goniometric scan, as performed in Sec II-A, was impossible for larger super-arrays. For the 2x2 super-array analysis, a 10x20 cm raster scan in multi-pixel power metering mode was performed at a 15-cm distance with the THz camera module. The camera field-of-view of 46° [3] then only limits the scene under view. Fig 2 shows the measured intensity profiles and the ray-tracing simulation results of the 2x2 super-array.

In the 2x2 super-array rhombus arrangement, the illumination aperture is approximately quadrupled at a 15-cm distance. A comparison between the total integrated power for the combination of the four source arrays and the sum of the separate ones (SA1 to SA4) verifies that the radiated power at 0.53 THz is quadrupled to 4 mW (6 dBm). The 10-dB FF in this experiment, however, is only increased to 46.1%, as just the two inner devices, SA3 and SA4, were rotated by 6.25 towards each other. The outer devices, SA1 and SA3, were mounted straight.

III. CONCLUSION

In this paper, we have investigated the concept of THz super-arrays to scale silicon integrated THz source arrays into large THz illumination apertures with high output power. Beam pattern profile characterizations of two different super-array configurations have been presented. It has been shown that the radiated power scales with the number of source array modules. However, in the system design of such multi-chip scaled super-arrays, there exists a trade-off between a high fill factor and a wide illumination aperture. The super-array approach offers valuable opportunities in the THz field; e.g., security screening will benefit from the availability of large super-arrays of low-cost silicon-based diffuse illumination sources. In the investigated device, its housing currently limits the minimum center-to-center distance. Packaging multiple chips on the same board, however, would enable to overcome this limitation and expand the system scalability and variability. Further, those incoherent System-on-Chip source array modules and their various configurations allow different types of diversity, such as spatial position, angle, frequency, or polarisation. This diversity can minimize the parasitic influence of the existing coherence in active THz imaging.

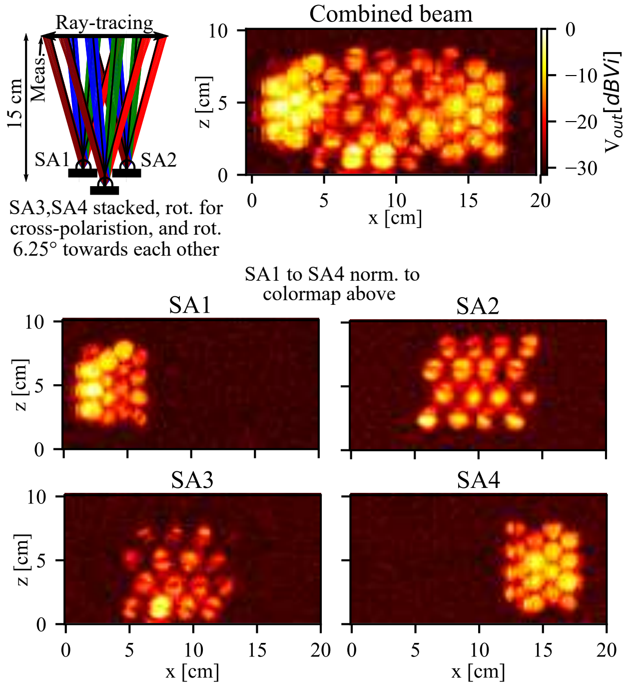

Figure 2. Ray-tracing simulation versus raster-scan measurement results of the 2x2 rhombus arrangement performed at a 15-cm distance for the combined beam and the single beams (SA1 to SA4). All the beam pattern profiles are normalized to the maximum of the combined beam and plotted in a logarithmic scale. The illumination aperture is quadrupled, the 10-dB FF is 46.1%, and the radiated power at 0.53 THz is 4 mW (6 dBm).

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