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A Plasmonic Array Architecture for Multi-Beam Spatial Multiplexing at THz Frequencies

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***Abstract*—A plasmonic array architecture with the ability to generate multiple independent, orthogonal beams at THz frequencies is proposed, analytically modeled and numerically demonstrated. The design leverages novel plasmonic device properties to perform discrete Fourier transform for the spatial domain in the analog regime with reduced complexity, and can be utilized to enable ultra-massive MIMO communications.**

I. Introduction

Terahertz (THz)-band (0.1-10 THz) communication is envisioned as a key wireless technology to fulfill the demand for increasing data rates and the need to accommodate denser networks [1]. THz-band communication, however, suffers from very high propagation losses. Further, despite many technological advancements, efficient high-power on-chip THz transceivers are still under development. These limitations restrict the communication distance drastically. One solution to this problem would be a dynamic, beamsteering antenna array. However, mainly due to a dearth of phase shifting elements that can operate at THz frequencies, such arrays have not been realized at frequencies above 300 GHz.

In this context, the utilization of two-dimensional (2D) nanomaterials, such as graphene, for novel THz devices has attracted the attention of the engineering community. Graphene supports highly confined electromagnetic (EM) waves known as surface plasmon polariton (SPP) waves, at THz frequencies, whose propagation properties can be tuned. Leveraging this, a fully plasmonic array architecture was proposed and analysed in [2] to combat the propagation loss, and open the door for ultra-massive (UM) MIMO communications, unleashing the full potential of the THz band. The plasmonic array architecture, shown in Fig. 1a, and explained in depth in [2], has several key advantages over conventional antenna arrays: 1) Individual power source and dedicated modulator for each radio frequency (RF) chain, with direct up-conversion from the analog base band to the THz carrier; 2) Complete phase and gain control at each antenna element; and 3) All the elements of the RF chain are composed of the same active material, i.e, graphene. For UM-MIMO, one approach is to facilitate multiple users through spatial multiplexing, by transmitting multiple data streams simultaneously in different directions. The application of a spatial inverse discrete Fourier transform (IDFT) across an N-element uniform linear array in transmit-mode is known to generate N orthogonal beams, thereby supporting N data streams [3]. However, a digital implementation of the concept that supports multi-GHz bandwidths will need multiple high bandwidth data converters, with large complexity and power costs. In this paper, we exploit the properties of our previously designed array to demonstrate a plasmonic multi-beam architecture at THz frequencies, where the IDFT operation is performed in the analog domain.

II. Methods

The multi-beam architecture, for $N = 4$, is presented in Fig. 1b. Through independent up-converters, we duplicate data streams to avoid signal path crossings and reduce design complexity from 16 phase controllers, as required in IDFT, to 7.

The design of the required array element is shown in Fig. 2. The present setup is shown in Fig. 2a, where a particular antenna element is shown. The signals from the independent input data streams are connected to the antenna through a plasmonic modulator and combiner. The modulator provides the required phase shift as per the architecture requirements. A combiner is utilized to ensure that all the signals are fed to the antenna in the same way, thereby minimizing spurious effects of the asymmetric geometry. A similar design is utilized for the rest of the array elements, with the data streams being duplicated as required.

The phase shifting modulator works as a function of the Fermi energy of the graphene layer, (i.e., the highest energy level occupied by electrons in graphene). This is controlled through an electrostatic DC bias [4]. Therefore, it is important to note that in the case of an all plasmonic array, it is not the individual number of graphene based modulators that are utilized, but the no. of electric contacts involved in the control of these that effect system complexity. Replicating multiple strips of graphene with the same electric contact is a trivial task. This is utilized to our advantage as shown in Fig. 2. In Fig. 2a, while there appear to be individual modulators for each data stream, the modulators which provide the same phase shifts are controlled by common control lines. The same functionality could be achieved by physically combining data streams into a common modulator for a butterfly structure, as in Fig. 2b.

Nonetheless, all the modulators that have the same required phase shift are controlled by the same control line without requiring additional electric contacts. Thus, the present setup is both easier to fabricate and control than an alternative.

III. Results

We present the multi-beam plasmonic array response in Fig. 3. It is seen that the array, designed at a *true* THz

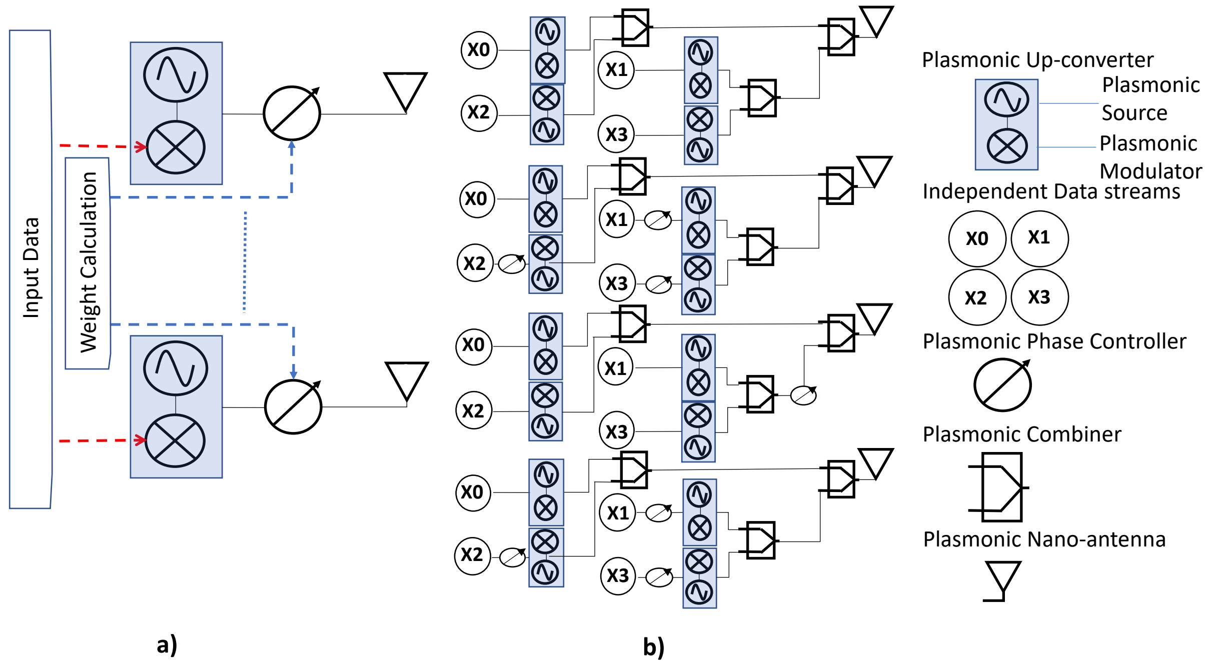

Fig. 1: a) Plasmonic array architecture proposed in [2]; and b) 4×1 array design for multi-beam functionality.

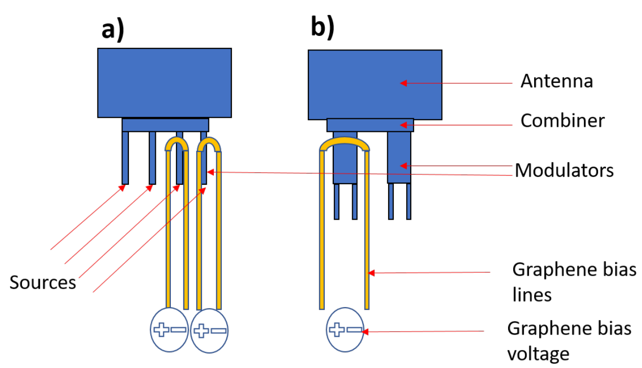

Fig. 2: a) Achieving the butterfly structure through replication of gating voltage bias; and b) A physical representation for the butterfly structure.

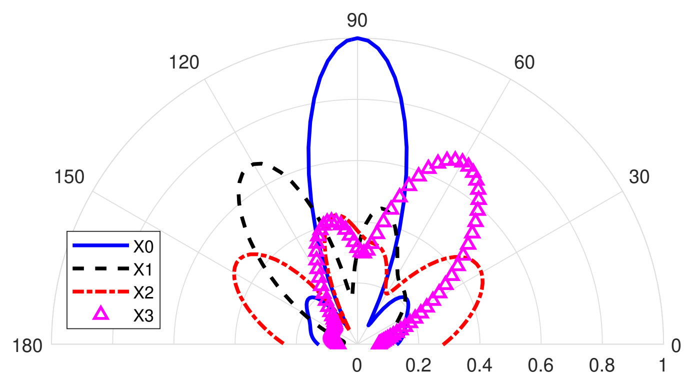

Fig. 3: Plasmonic array far-field pattern illustrating spatial multiplexing at THz frequencies.

frequency of 1.03 THz (i.e., the first transmission window above 1 THz), exhibits the desired multi-beam response. While the array can simultaneously multiplex multiple data streams in different directions, it is important to note that the power output is not uniform. This is due to the fact that the phase shifters are graphene based, and therefore there is an inherent power attenuation as the SPP waves are transmitted. Therefore, for higher phase tuning, the loss is increased, thereby relating to unequal signal strengths. If desired, for uniform beam strengths, it is possible to truncate the stronger beams through power allocation at the source itself (given the current lack of amplifiers at THz frequencies). Additionally, since the beam pattern corresponding to X2 is endfire, there is inherent attenuation due to the broadside directivity of the nano-antenna, as it is designed similar to a patch antenna.

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