Hybrid Graphene/semiconductor Plasmonic Technology For Ultra-broadband Terahertz Communications

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Abstract—**In this paper, the state of the art and progress towards building a complete plasmonic front-end for Terahertz communications is described. The discussed system architecture, whose components rely on the properties of graphene and III/V semiconductors, is able to generate, modulate, radiate and, reciprocally, detect and demodulate THz signals with multi-GHz bandwidths, needed for next generation communication systems.**

I. Introduction and Background

OVER the last few years, wireless data traffic has drastically increased due to a change in the way today's society creates, shares and consumes information. In parallel to the growth in the number of interconnected devices, there has been an increasing demand for higher speed wireless communication. In particular, wireless data rates have doubled every 18 months for the last three decades [1]. Following this trend, *Terabit-per-second (Tbps) links* are expected to become a reality within the next five years.

In this context, *Terahertz-band (0.1 to 10 THz) communication* has been envisioned as a key wireless technology to satisfy the need for much higher wireless data rates [2], [3]. The THz band supports huge transmission bandwidths, which range from almost 10 THz for distances below one meter, to multiple transmission windows, each tens to hundreds of GHz wide, for distances on the order of a few tens of meters. Nevertheless, this very large bandwidth comes at the cost of a very high propagation loss [4]. For many decades, the lack of compact high-power signal sources and high-sensitivity detectors able to work at room temperature has hampered the use of the THz band. However, many recent advancements are finally closing the so-called THz gap.

To date, different technologies have been considered to enable practical THz-band communications. In an *electronic approach*, III–V semiconductor technologies, such as indium phosphide heterojunction bipolar transistor technology, have demonstrated record performance in terms of output power, noise figure, and power-added efficiency at sub-THz frequencies, and are quickly approaching the 1 THz mark [5], [6]. These systems commonly rely on frequency-multiplying chains to up-convert a multi-GHz local oscillator to THz frequencies. Power loss due to the generation of non-desired harmonics and limited gain of these devices when approaching true THz frequencies hamper the energy efficiency and limit the feasibility of this technology for higher frequencies. In an *optics or optoelectronic approach*, quantum cascade lasers are clear potential candidates for high-power THz-band signal generation [7], [8]. These lasers can yield THz emission across a broad spectrum, offering output in the range of tens of milliwatts at cryogenic temperatures. However, they suffer from poor performance at room temperature.

A promising approach to realizing THz communications is to leverage the properties of plasmonic materials. For example, THz-frequency plasmons can be generated in the channel of a high-electron-mobility transistor (HEMT) by means of electrical or optical pumping [9], [10]. These plasmons are sustainable at cryogenic temperatures, but quickly decay at room temperature due to phonon-induced overdamping. Moreover, efficiently radiating these plasma excitations directly from the HEMT has proven difficult. In this direction, the use of plasmonic nanomaterials such as graphene has been proposed. Graphene is a two-dimensional carbon material that has excellent electrical conductivity, making it very well suited for propagating extremely-high-frequency electrical signals [11]–[13]. Moreover, graphene supports the propagation of THz surface plasmon polariton (SPP) waves. This is a very unique property, as SPP waves only propagate in conventional plasmonic materials in the infra-red and above.

Motivated by these properties, graphene-based plasmonic devices for THz-band communications have been recently proposed. In this paper, we provide an overview of the state-of-the-art and our group's latest contributions to building a complete plasmonic front-end able to generate, modulate, radiate, detect and demodulate THz signals.

II. Contribution, Results and Conclusions

In Fig. 1, the block diagram of a complete hybrid graphene/semiconductor plasmonic front-end is shown. The first element is the THz SPP source. There are different mechanisms to excite SPP waves on graphene. In [14], we proposed a novel hybrid graphene/semiconductor HEMT structure which can electrically excite SPP on graphene. The working principle of the proposed device relies on the Dyakonov-Shur instability [15] to excite a plasma wave in the HEMT channel, which then is utilized to launch a SPP wave on the graphene layer. In this design, the tunability of the graphene layer Fermi energy is leveraged to maximize the coupling between the plasma wave and the SPP wave. Another mechanism to excite SPP waves on graphene relies on the use of grating gated structures. For example, illuminating a grating-gated structure with a QCL would result in a SPP wave that propagates

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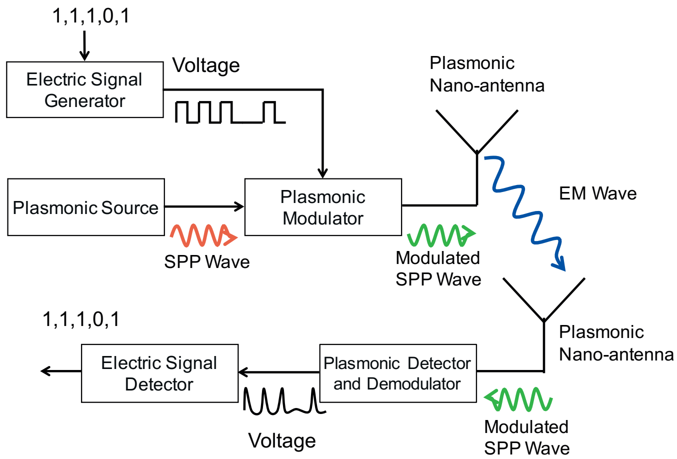

Fig. 1. Block diagram of a hybrid graphene/semiconductor plasmonic front-end.

well beyond the gated cavity [16], [17]. In both cases, these structures can work reciprocally as THz detectors.

Besides the THz signal source, a key element to enable practical THz communication systems is the modulator. As mentioned before, a key advantage of the THz band is its very large usable bandwidth, ranging from hundreds of GHz and up to a few THz. To benefit from such bandwidth, signal modulating devices with equally large modulation bandwidths are needed. The use of graphene to develop THz SPP modulators has been proposed both in on-chip [18] and free-space [19] designs. As opposed to traditional electronic modulators based on harmonic or sub-harmonic mixers, plasmonic modulators exhibit a much higher energy efficiency, as no energy is lost in harmonics. Compact systems for direct downconversion of the modulated signals are needed in reception.

After modulation, the SPP wave is radiated by means of a graphene-based plasmonic nano-antenna array. The utilization of graphene for both modulator and antenna minimizes the internal losses, maximizing the radiated power. As we first proposed in [20], a graphene-based plasmonic nano-antenna can be engineered to efficiently radiate at THz-band frequencies. However, given the expected low radiated power of a single nano-antenna, we propose to investigate plasmonic nano-antenna arrays. Mutual coupling between plasmonic elements needs to be characterized [21], and used to guide the design and integration of elements. For all these devices, besides the conceptual design and analytical modeling, there are several challenges related to the actual fabrication and integration, which need to be addressed in a vertically-integrated approach.

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