Plasmonic On-Chip Antenna Enabling Fully Passive sub-THz-to-Optical Receiver for Future RoF Systems

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Abstract: We demonstrate a fully-passive on-chip antenna integrated plasmonic modulator receiver with a built-in field enhancement of 10'000 around 235GHz making RF electronics redundant. Transmission of up to 80Gbit/s in a wireless sub-THz link is shown.

1. Introduction

Wireless communication systems have to follow the ever-growing demand for higher data rates. Due to spectral efficiency limitations, high channel capacities require high bandwidths, which in turn requires the use of free spectral bands at higher carrier frequencies. Recent research therefore has focused on the millimeter-wave (mm-Wave, 30-300 GHz) or sub-Terahertz (sub-THz, 100-300 GHz) regimes. The high carrier frequency promises high data rates in excess of 100 Gbit/s to tackle the data demand.

Over the last decade, various demonstrations of future communication links based on the sub-THz regime have been demonstrated. Recently, wireless sub-THz transmissions have been showing data-rates in excess of 100 Gbit/s over distances of 100 m [1]–[3]. However, all of these approaches have been relying on conventional radio frequency (RF) electronics such as external RF/mm-Wave antennas, up-mixing or down-mixing and electronic amplification stages to transition from/onto the optical domain. These devices are often bandwidth limited and hinder the ease of integration into the existing fiber network.

For this reason, more recently full photonic systems have been used to overcome the RF bottleneck while offering seamless integration into existing fiber optical networks [4]–[7]. While [6], [7] demonstrated the potential for high-capacity of sub-THz systems, next generation wireless communication should become more compact and rely on an integrated device approach compatible with silicon [5], offer low power consumption or ideally do not require any electrical interfaces. All of which should enable low-cost and reliable manufacturing. Recently, a plasmonic electro-optic modulator antenna concept has been proposed [4]. By bypassing any signal propagation and conversion in the electronic domain and instead relying directly on the optical domain, such a device is practically exclusively limited in terms of bandwidth by the antenna itself. This concept has achieved direct conversion of RF to optical frequencies at high sensitivity, enabled by high field enhancement values of 90'000, and small footprints [5]. Employing plasmonic modulator antennas at a 60 GHz RF carrier frequency, 20 Gbit/s and 10 Gbit/s line rates over 1 m and 5 m free space distances have been demonstrated, respectively. However, the carrier frequency of such devices has to be pushed into the sub-THz to potentially reach higher data capacity and thereby enabling new applications. Recently, a theory on antenna coupled plasmonic modulators [8] has suggested that the concept can be applied to produce efficient sub-THz-to-optical conversion. However, the carrier frequency for this application of such devices has to be pushed into the sub-THz to potentially reach higher data capacity and thereby enabling new applications.

In this work, we achieved direct sub-THz-to-optical conversion with high field enhancement by using a co-integrated plasmonic modulator with a four-leaf-clover (FLC) antenna [8]], fabricated on Polariton's Plasmonic PIC platform [9]. The antenna reaches a field enhancement of 10'000 at a carrier frequency of 235 GHz, making it a sensitive direct sub-THz receiver without the need for external antennas or electrical amplifiers. In this work, we demonstrate a plasmonic on-chip antenna enabling a direct sub-THz-to-optical conversion with a high field enhancement by using a co-integrated plasmonic modulator with a four-leaf-clover (FLC) antenna [8]. The field enhancement values are inversely proportional with the frequency of operation. Despite operating at the frequency band around 235 GHz, the antenna reaches a field enhancement of 10'000, making it a sensitive direct sub-THz receiver without the need for any bulky external antennas or electrical amplifiers. The device comprises of a co-integrated plasmonic modulator with a four-leaf-clover (FLC) antenna. Further, as a proof of concept, we mimic a wireless link by employing low gain antenna over a distance of 1 m and showing successful transmission of 80 Gbit/s. Remarkably, the receiver system based on the plasmonic antenna operated without any RF electronics benefiting from its inherent high plasmonic field enhancement. This plasmonic device is therefore a compact direct receiver with a small footprint of 0.018 mm^2. Moreover, it is compatible with standard silicon technologies. The measured response is closely following the simulated response and is also scalable to higher THz frequencies, offer a solution for next generation wireless communication systems.

2. On-chip Fully Passive Plasmonic Antenna Receiver Based System Description

Our proof-of-concept experimental setup was designed to test the on-chip plasmonic antenna with built-in field amplification. To represent a real-world scenario of a wireless communication application, we established a fiber–wireless–fiber link, as illustrated in Fig. 1(a). The free space path loss of the link is 80 dB, while the link gain is 50 dB (the TX horn antenna and the lens). First, an electrical signal based on a quadrature amplitude modulation (QAM-4) is encoded onto an optical carrier ($f_{c_{Tx}}$) using an in-phase and quadrature (IQ) modulator. Subsequently, the optical signal is converted into a sub-THz wireless signal by beating it with a local oscillator in a uni-travelling carrier photodiode (UTC-PD). The RF signal is then amplified and fed into a horn antenna. The wireless signal (f_{subTHz}) is then mapped onto a the plasmonic antenna by means of a high-density polyethylene lens. The core of the link is the on-chip plasmonic modulator antenna-based receiver as depicted in Fig. 1(b). This device comprises a plasmonic electro-optic modulator and an antenna segment. A CW optical carrier at $f_{c_{Rx}}$ is fed into the plasmonic modulator via an optical waveguide. The incoming sub-THz field is captured by the antenna and transformed into an electric field across a plasmonic slot (E_{slot}) between the modulator plates. This field is then used in the plasmonic modulator to encode the received information onto an optical signal and fed into the optical waveguide. The optical spectrum measured at the output of the optical waveguide of the plasmonic antenna is shown in Fig. 1(c). The modulated upper and lower sidebands are centered at $f_{c_{Rx}}$±235 GHz with -33 dBc sideband ratio.

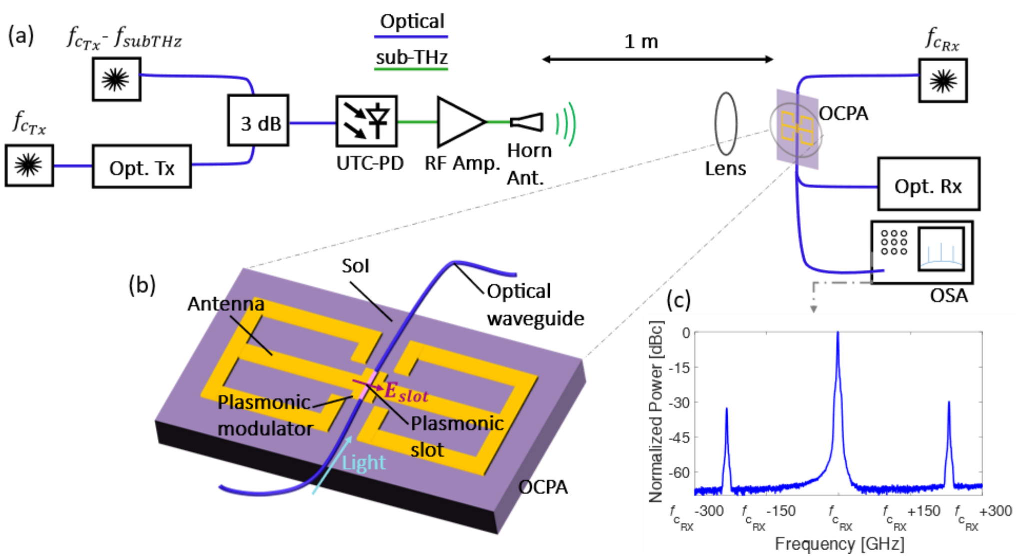

Fig. 1: (a) The proof-of-concept experiment setup for wireless data transmission. Opt. Tx, optical transmitter; UTC-PD, uni-travelling carrier photodiode; RF Amp., radio frequency amplifier; OCPA, on-chip plasmonic antenna; Opt. RX, optical receiver; OSA. (b) The concept of the plasmonic modulator antenna. (c) The normalized optical spectrum measured at the output of the optical waveguide of the plasmonic antenna.

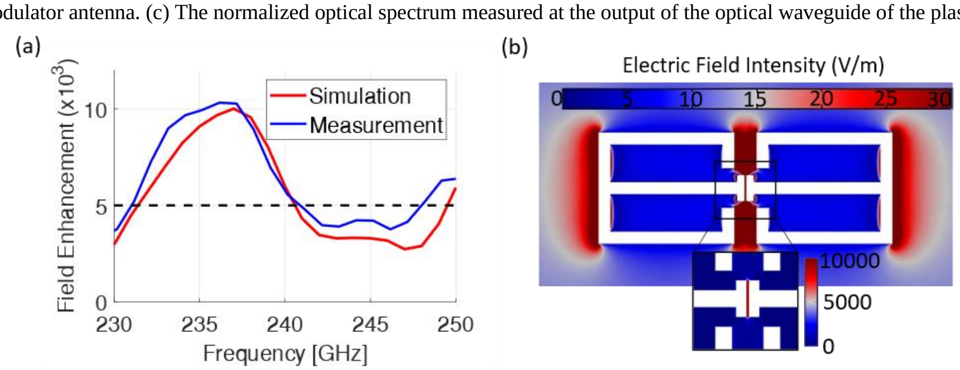

Fig. 2: Antenna field enhancement (a) Simulated (red line) and measured (blue line) field enhancement responses of the FLC antenna. The simulated response has been reduced by a factor 2. (b) Electric field intensity distribution over the FLC antenna with the focus on the plasmonic slot where the built-in field amplification occurs.

The primary objective in designing the antenna and the modulator is to inherently amplify the field in the plasmonic slot that eliminates the necessity for RF electronics. The four-leaf clover (FLC) antenna is selected due to its high sensitivity performance [8], [10] and is fabricated on a silicon-on-insulator (SoI) wafer. Fig. 2(a) presents the simulated (red line) and measured (blue line) field enhancement performances of the FLC antenna over the frequency band of 230 and 250 GHz; both frequency responses are fitting well. In addition, the near electric field response of the FLC antenna at 235 GHz is shown in Fig. 2(b). The full-wave resonance behavior is observed; electric field is maximized at the ends of the FLC arms and in the middle where the plasmonic slot of 100 nm width is located. In Fig. 2(b), a detailed close-up, showing a uniform distribution of electric field values—around a factor 10’000 larger than the incident field strength —at the plasmonic slot is given. As a last step, the electrical signal is received using a coherent optical receiver.

3. Free-Space Wireless Communication Link

To evaluate the wireless link between the transmitter and receiver, tests were conducted in a 1 m link. The results from the free space fiber-wireless-fiber data experiment, presented in Fig. 3, demonstrate the link performance. Line rates of 64 Gbit/s and 80 Gbit/s were achieved for the 1 m link, with bit-error rate (BER), general mutual information (GMI) and achievable information rate (AIR) is shown in Fig. 3. AIR was calculated by multiplying the GMI value with the symbol rate. The normalized general mutual information for the 64 Gbit/s as well as the 80 Gbit/s measurement stay below the 25% soft decision-forward error correction threshold given in [11].

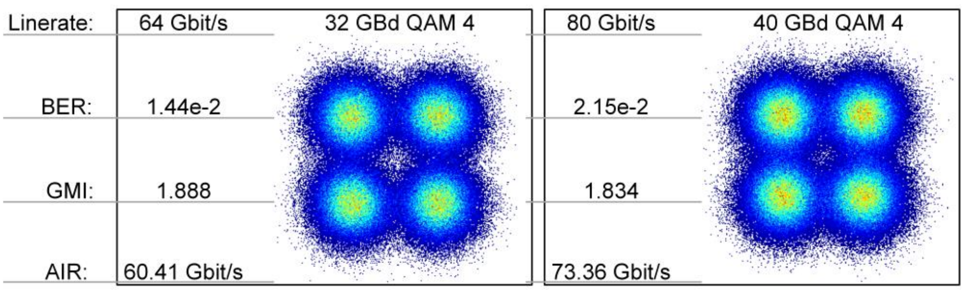

Fig. 3: Constellation diagrams, BER and GMI values of the received QAM-4 signal for data rates of 64 and 80 Gbit/s.

4. Conclusion

In summary, our integration of an on-chip plasmonic modulator and a FLC antenna enables direct sub-THz-to-optical conversion with its built-in field amplification of 10’000 at 235 GHz. Facilitating data rates of up to 80 Gbit/s without RF electronics on the receiver side, scalability and extremely small footprint (0.018 mm²) showcase its potential. The results demonstrate that this concept can pave the way for high-speed, compact, and seamlessly integrable devices for future wireless communications.

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6. References

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