Plasmonics in Future Radio Communications: Potential and Challenges

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Abstract

Plasmonics is increasingly emerging as an alternative to photonics. It has the potential to revolutionize the field of communications and radio science as it gives the user access to devices with highest bandwidths, on a most compact footprint and at lowest power consumption. And while the potentials are many, the technology also has its challenges. So, for instance, plasmonic fabrication requires a technology that can handle features with a 10 nanometer precision and better. Another aspect relates to plasmonic losses. Losses are inherent to the technology that is why device sizes need to be kept small and RF-to-light interaction must be maximized.

In this review, we summarize the state in the field and comment on potentials and challenges of plasmonics in view of communications and radio science applications.

1 Introduction

Future access networks are going to heavily rely on sub-THz or THz wireless connections. These frequencies are of interest as they allow the transmission of much higher capacities. Under line-of sight conditions, sub-THz and THz beams behave fairly similar to an optical beam. Yet, unlike optical beams they transmit better under adverse weather conditions such as fog [1], snow [2] or haze [3].

A possible scenario is depicted in Fig. 1, see Ref. [4]. The figure shows central offices (COs) that distribute the signals over fiber to remote antenna units (RAUs). In some instances, radio-over-fiber links will be deployed. Ideally, they should transmit signals at fiber-optic speed, i.e. 100s of Gbit/s.

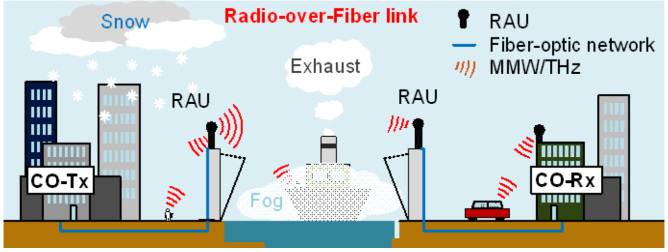

Fig. 1. A scenario of a future network comprising of optical as well as sub-THz links. Signals are typically distributed from a central office (CO) through a fiber network. The optical signals connect radio-antenna units (RAUs), which then distribute sub-THz wireless signals to its customers. To overcome obstacles a radio-over-fiber link might be deployed. It offers seamless and transparent transmission of a signal trough a fiber to a wireless sub-THz channel and back to an optical fiber. Figure adapted from Ref. [4].

In this paper, we give an outlook on future highest-speed radio-over-fiber (RoF) networks and possible implementations that are taking advantage of plasmonics. In particular, we will discuss a recent record radio-over-fiber link transmission over a distance of 115 m with a record high 200 Gbit/s capacity [4]. Key elements within such a plasmonic RoF are discussed.

2 Plasmonic Devices

Plasmonics has been envisioned as an advanced technology to replace photonics for quite a while [5-8]. And while its promises have been a most compact size and ultrafast operation, the first high-speed data-operation – to the best of our knowledge - has only been demonstrated in 2013 [9]. Key to the success was a new scheme, in which plasmonics was used to confine light to a narrow plasmonic slot waveguide but where the nonlinear interaction was not due to the plasmonics nature. The active operation was passed on to a nonlinear material within the plasmonic slot-waveguide.

Depending on the application, plasmonic slot waveguides can be combined with a variety of nonlinear materials [10].

- For highest-speed **modulators**, a plasmonic slot-waveguide configuration with a Pockels-effect material in the slot has proven to be almost ideal [11]. This way electro-optical modulators with bandwidths in excess of 500 GHz [12] and operation up to 2.4 THz [13] have already been shown. As an active material one may use an organic material [14] or an inorganic material such as BTO [15].
- For **detectors**, the photoconductive-effect has been successfully exploited. Using germanium in plasmonic slot waveguides, flat frequency responses up to 100 GHz and responsivities of 0.36 A/W were found [16]. In another instance, the photoconductive effect was used too in a bolometric graphene detector to detect signals with a flat frequency response up to 100 GHz and a responsivity of 0.55 A/W [17].

3 Plasmonic Devices for Radio Communications

Key elements in a radio network are the RAU transmitter (Tx) and the RAU receiver (Rx). They translate an optical signal to the sub-THz or receive the sub-THz and transfer the information back to the optical world, respectively.

RAU-Tx side: Current RAU-Tx often translate an incoming optical signal to the electronic domain and then map it to the RF domain. At higher frequencies such solutions become prohibitively expensive. As a solution the community is increasingly resorting towards directly converting the optical signal to the RF domain by means of heterodyne mixing of the incoming signal with a local oscillator within an ultrafast photodiode. Typically, uni-traveling-carrier (UTC) photodiodes are used [18]. UTC PDs typically offer at a highest frequency (e.g. at 300 GHz) a good frequency response of e.g. 0.25 A/W within a window of about 100 GHz. More recently, as an alternative, the first highest speed plasmonic detectors have emerged. They offer a flat frequency response up to highest speed. Alternatively, graphene is increasingly maturing. Most reently, graphene detectors with 300 GHz have been introduced [19]. This new generation of photodetectors based on 2D materials might replace the more traditional UTC photodiodes. As an advantage, the graphene photodetectors offer a flat frequeny response accross the whole spectral window from a few GHz up to e.g. 300 GHz. However, neither the current plasmonic nor graphene photodetectors do offer sufficently high output powers such as needed for a reliable operation and a considerable research effort has still to go into this development.

RAU-Rx side: Current RAU-Rx units almost without any exception (at least at high speed) down-convert the sub-THz signal to the electrical baseband and then are in need to map it back to the optical domain [20-23]. Such a down-mixing to the electrical domain could be avoided by means of electro-optical modulators. Unfortunately, typical modulators only offer bandwidths up to 100 GHz at best. However, in 2015 a direct RF-to-optical conversion relying on plasmonic modulators was introduced [24]. A possible implementation such as used to detect a 2.4 THz signal is depicted in Fig. 2, see [13]. Fig. 2 shows two plasmonic phase-shift (PPS) modulators arranged in a Mach-Zehnder interferometer (MZI) configuration. They are propelled by the THz electrical signal that is received by two four-leaf-clover antennas. In the meantime, such plasmonic RAU-Rx schemes have already been used to demonstrate down-mixing of signals at 300 GHz [25]. A unique advantage of the plasmonic antenna down-mixing is the built-in amplification. The amplification is due to two effects [24]. The amplification is first through the antenna gain (10-20 dB) and then through the plasmonic field enhancement obtained when the THz field drops off across the narrow plasmonic slot (a 30 – 40 dB gain). More precisely, the induced phase modulation $\Delta\varphi$ in the PPSs is enhanced to the same extent as the field is enhanced [24], i.e.

$$\Delta\varphi \propto FE \cdot E_{\mathrm{RF}}(t).$$

Plasmonic antenna enhancements in the order of 49 dB have already been shown [26].

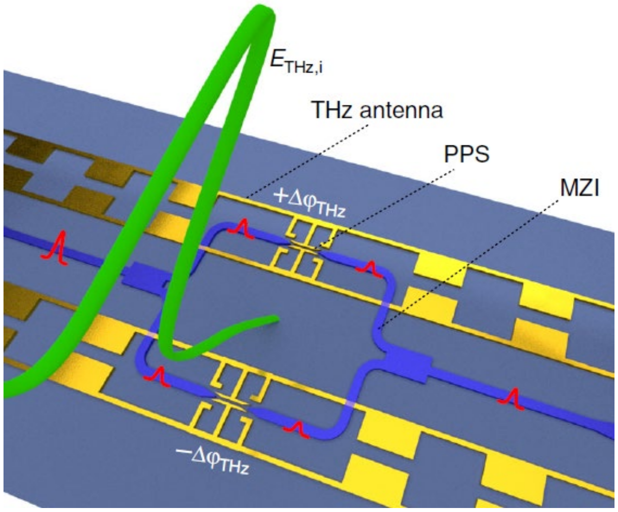

Fig. 2. THz detector with antenna in a plasmonic Mach-Zehnder interferometer (MZI) configuration. An incident THz field $E_{\mathrm{THZ,i}}$ is detected by two four-leaf-clover antennas. The antenna translates the fields onto plasmonic/optical fields that travel in the slots of plasmonic phases shifter (PPS) modulators. The PPS are arranged within a MZI configuration. See [13].

4 Radio-over-Fiber Transmission by Plasmonics

Next generation 6G systems are in need for highest capacity wireless solutions that allow for transmission over the longest possible distances. Line rates at and above 100 Gbit/s [23, 27-37] for distances up to 20 m [27], a line rate of 132 Gbit/s over 110 m [36], and more recently a line rate of 192 Gbit/s over 115 m [4] have been reported. Higher capacity transmissions have also been shown. They typically take advantage of polarization and/or MIMO multiplexing [38, 39].

However, electronic solutions have limitiations. More precisely, electronics suffer from

- Limitations to operate at sub-THz carrier frequencies f_{THz}
- Difficulties to support broad fractional bandwidths Δf at high carrier frequencies f_{THz}.

The important question then is as of which solution enables transmission at highest capacities over longest distances. It is thereby worth discussing the most recent record transmission of 150 Gbit/s data over 115 m [4]. In this experiment transpartent optical-to-RF-to-optical transmission concepts have been employed, i.e. a direct downmixing at the RAU Tx from the optical to the RF and direct upmixing of the RF-to-optical at the RAU Rx. This way electronic interfaces with their limitations can be circumvented.

Key to the success have been plasmonic modulators with built-in antenna [24]. The concept has first been tested for the direct upconversion from the RF to the optical domain at moderate 20 Gbit/s [26]. And while in said first experiment the transmission speed has mostly been limited by device losses, much higher speeds have been achieved in a more recent experiment. In this experiment, record transmission over 115 m with line rates of 150 Gbit/s were demonstrated [4].

Subsequently we will discuss said recent 150 Gbit/s plasmonic radio-over-fiber link experiment.

The experimental setup for demonstrating the link is illustrated in Fig. 3. It comprises a 6 km optical fiber span, a subsequent 228 GHz carrier wireless link of 115 m length, and an optical fiber link of 4 km. Key elements of the link are the

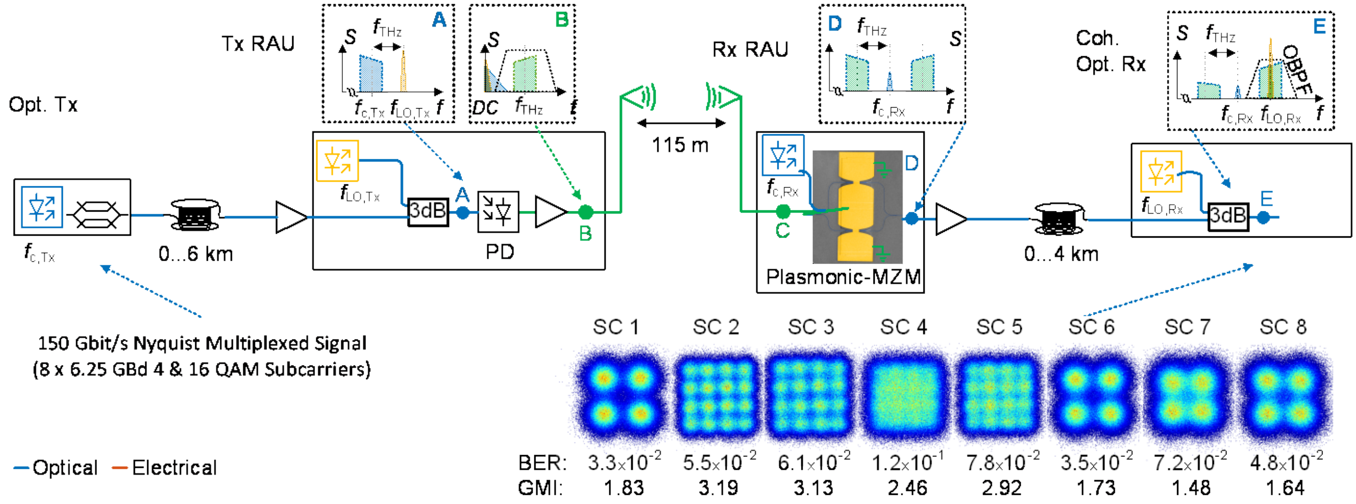

Fig. 3. Demonstration of 115 m THz wireless data communication experiment embedded in a fiber-optical network. In the optical transmitter (Opt. Tx.), a Nyquist frequency-division multiplexed electrical data signal is encoded on to a 1550 nm optical carrier ($f_{\mathrm{c,Tx}}$). After mapping the data to the THz domain by means of an UTC-PD, the signal is emitted to far-field by a directive antenna and propagates over 115 m wireless distance. At the Rx RAU, the THz signal is received by a second antenna and directly drives a plasmonic modulator (no re-amplification needed). The optical spectrum after the plasmonic MZM consists of its two modulated sidebands and a carrier, see point D. After amplification in an EDFA, the signal is transmitted over a second fiber span and directly mapped to baseband by a narrow-bandwidth local oscillator ($f_{\mathrm{LO,Rx}}=f_{\mathrm{c,Rx}}+f_{\mathrm{THz}}$) in the coherent receiver (Coh. Opt. Rx). The measured digital constellation diagrams of each subcarrier (SC) of the 50 Gbaud 8-Nyquist-FDM signal with a bit-loading of [2, 4, 4, 4, 4, 2, 2, 2] bits/symbol are shown, achieving a total net data rate of 114.91 GBit/s at a line rate of 150 Gbit/s. See Ref. [4] for details.

transmitter (Tx) RAU with the optical-to-sub-THz converter (O-THz Conv.) and receiver (Rx) RAU.

In more detail, we have on the left the optical transmitter (Opt. Tx). The optical Tx consists of an IQ modulator, which encodes a Nyquist frequency division multiplexed (FDM) electrical data signal onto an optical carrier ($f_{\mathrm{c,Tx}}$) [40]. Each subcarrier transmits 6.25 GBaud with either a 4QAM or 16QAM modulation format. In total we have 150 Gbit/s. The Nyquist FDM modulation format was chosen because this allowed for adapting the modulation format and power of each subcarrier to the frequency responses of the antenna system (bit- and power loading).

Behind the optical Tx, the data signal has been transmitted through a 6 km standard single mode fiber (SSMF) span.

At the Tx RAU the optical data signal has been first boosted by an erbium doped fiber amplifier (EDFA) and coupled to a free-running laser detuned by the wireless carrier frequency f_{THz} ~= 230 GHz. After power- and polarization alignment, the combined signals were fed to a UTC-PD, whereby heterodyne mixing the data signal is down-mixed to the sub-THz frequency range. The overall optical power entering the UTC-PD was between 8 and 14 dBm to provide THz output powers in the order of -24.5 to -12.4 dBm. Behind the UTC-PD, a THz medium power amplifier (MPA) has boosted the THz data signal to 11.5 dBm before being fed to the antenna.

The sub-THz signal has then been transmitted over the free-space link of 115 length. To compensate for the free space loss of 121 dB, two highly directive antennas were employed. The link gain provided by the THz antennas were in the order of 109 dB. Thus, the free space net-transmission loss thereby was 12 dB.

At the Rx-RAU, the received THz data signal has been received by the plasmonic antenna and directly fed to the plasmonic Mach-Zehnder modulator (MZM), where it was mapped to the optical domain [41]. In the following the signal has been transmitted over a 4 km fiber to a remote receiver.

At the remote receiver, a coherent receiver was employed to map the signal back to the baseband. For this the local oscillator is tuned to one of the sidebands carrying the RF information. The signal is then extracted by means of an intradyne detection scheme.

Lastly, the signal is analyzed by an offline DSP stage consisting of Nyquist FDM demultiplexing, matched filtering, timing recovery, carrier and phase recovery, and linear equalization with 99 taps. The measured generalized mutual information, (GMI) [42], bit-error-ratio (BER), and maximum net data rate after successful FEC decoding are used to evaluate the transmission performance.

The constellation diagrams, BER and GMI of each subcarrier of the transmission experiment are depicted in Fig. 3. At a line rate of 150 Gbit/s, a net-data rate of 114.91 Gbit/s was found. This value is obtained by multiplying the average GMI of 2.29 bits/symbol of the 8 subcarriers by the subcarrier-symbol rate of 6.25 GBaud.

It should be mentioned that we also tested the system performance when adding an electrical RF-amplifier at point C in Fig. 3. And indeed, by boosting the received sub-THz signal before the modulator, line rates of 192 Gbit/s with net-data rates of 164.4 Gbit/s could be transmitted over 115 m. This is an improvement. Yet, we consider the overall advantage to be moderate. Particularly, as the plasmonic transmission concept is still new and the system has not yet been optimized.

5 Conclusions

In this paper we have reviewed RoF links employing plasmonics. We have thereby discussed plasmonic photodetectors and modulators that offer the necessary bandwidth, and sensitivity to enhance next generation radio communications systems.

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