Wireless Transmission at 0.3 THz Using Direct THz-to-Optical Conversion at the Receiver

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Abstract *We report a THz wireless link at 0.2885 THz which is embedded in a photonic network. An ultra-broadband plasmonic modulator directly converts the THz signal to the optical domain. We transmit QPSK data with line rates up to 50 Gbit/s.*

Introduction

Wireless networks have to cope with an exponential increase in mobile data traffic, which is predicted[1] to account for 63 % of the global internet traffic by 2021. To meet the underlying capacity challenges, wireless communication networks will have to handle data rates of tens or even hundreds of Gbit/s per link. This can only be accomplished by exploiting frequency windows of low atmospheric attenuation[2] in unallocated spectral ranges beyond 0.275 THz. From a networking perspective, future wireless links need to be intimately integrated into fiber-optic infrastructures, which calls for seamless connection of optical fibers to THz transmitter (Tx) and receiver (Rx) front-ends. At the Tx, optoelectronic conversion of data streams from the optical to the THz domain has been demonstrated to offer a variety of advantages[3] such as wideband tunability of the carrier frequency and the ability to exploit advanced modulation formats and multiplexing schemes that are widely used in state-of-the-art optical communications. As an example, wireless transmission at 100 Gbit/s has previously been demonstrated[4] by direct optical-to-THz (O/T) conversion of a wavelength-division multiplexing (WDM) signal in an ultra-fast uni-travelling-carrier photodiode (UTC-PD). In contrast to that, direct THz-to-optical (T/O) conversion of data signals has not yet been shown.

In this paper, we demonstrate a wireless link that is seamlessly integrated into a photonic network, exploiting direct O/T and T/O conversion at the Tx and the Rx. The wireless link operates at a carrier frequency of 0.2885 THz with a maximum line rate of 50 Gbit/s, bridging a distance of 16 m. The THz signal is generated by O/T conversion in a UTC-PD. At the receiver, the THz signal is converted to the optical domain by using an ultra-broadband plasmonic-organic hybrid (POH) modulator[5,6]. The POH modulator has a footprint of only 500 μm^2 and is suitable for high-density integrated photonic circuits. To the best of our knowledge, this is the first demonstration of direct conversion of a THz wireless data signal to an optical carrier without prior down-conversion to the baseband or an intermediate frequency.

Plasmonic-organic hybrid (POH) modulator

In our experiment, T/O conversion is accomplished by an ultra-broadband POH Mach-Zehnder modulator[7,8] (MZM), which is fabricated on the standard silicon-on-insulator (SOI) platform with a device layer thickness of 220 nm, see Fig 1. Each arm of the MZM comprises a metallic nanoslot of 75 nm width that forms a plasmonic slot waveguide of length *L* between gold electrodes, Fig. 1(a). A pair of silicon (Si) waveguide tapers (blue) allow conversion between the Si photonic mode and the tightly confined plasmonic mode (Fig. 1(a), inset on top right) in the metallic slot. The RF signal coupled through the ground-signal-ground contacts of the MZM drops in the metallic nanoslot (Fig. 1(a), inset on bottom left), leading to a strong overlap between the optical and RF electric fields. The modulator is functionalized by filling the slot with an electro-optic (EO) cladding material (SEO100 from Soluxra, LLC). The active chromophores are aligned (green arrows in Fig 1(b)) through a one-time poling process by applying a DC electric field U_{pol} at an elevated temperature. The modulating electrical drive voltage U_{d} in Fig. 1(c) is oriented (red arrows) parallel to the chromophore alignment in one arm of the MZM and antiparallel in the other one, leading to a push-pull operation of the MZM. Plasmonic modulators are predicted to have operating bandwidths[8] up to 1 THz as the slot capacitance (~ 3 fF) is connected to the $50\,\Omega$ signal source through a highly conductive metal film leading to a large RC corner frequency. In a recent experiment[9], we demonstrated a flat frequency response of POH MZM up to at least 0.325 THz as shown in Fig. 1(c).

Experimental Setup

The fiber-to-fiber link consists of an O/T converter, the wireless link and a T/O converter,

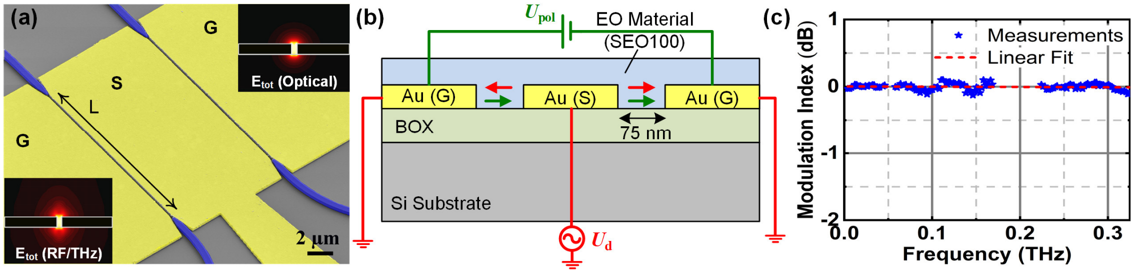

Fig. 1: Plasmonic-organic hybrid (POH) modulator. (a) Colorized scanning electron micrograph of POH Mach-Zehnder modulator (MZM) showing two plasmonic slot waveguides of length *L* between ground-signal-ground (GSG) electrodes. Tapers are used at the transisions between the silicon photonic strip waveguides and the plasmonic section, enabling efficient conversion between the photonic and the plasmonic modes. Mode profiles of the optical quasi-TE field (top right) and the RF/THz field (bottom left) showing strong confiment to the metallic slot. (b) Cross-section of POH MZM. During the poling process, a DC voltage U_{pol} (green) is applied across the floating ground pads at an elevated temperature, thereby aligning the EO chromophores (green arrows) with respect to the applied field. The orientation of the dipoles is retained after cooling down the device. A modulating drive voltage U_d (red) across the MZM induces fields (red arrows) parallel to the EO chromophore orientation in one arm, and antiparallel in the other arm of the MZM leading to a push-pull operation. (c) Frequency response of POH MZM.

Fig. 2(a,b). A schematic of the O/T converter is depicted in Fig 2(a). An arbitrary-waveform generator (AWG, Keysight M9505A) with a sampling frequency of 90 GSa/s is used to generate a quadrature phase-shift keying (QPSK) data signal using a pseudo-random binary sequence (PRBS) with a length of 2^{11}-1. The electrical is coupled to an IQ electro-optical modulator that modulates a continuous-wave (CW) carrier provided by an external cavity laser (ECL) at a frequency $f_0 = 193.3\,\mathrm{THz}$. The IQ modulator is operated at its null-point in order to supress the carrier at f_0. The modulated signal is superimposed with an unmodulated CW carrier at $f_{\mathrm{Tx,LO}} = 193.0115\,\mathrm{THz}$. Both optical waves are photomixed in a UTC-PD[10] that generates a modulated THz carrier at the difference frequency, $f_{\mathrm{Tx,THz}} = \left|f_0 - f_{\mathrm{Tx,LO}}\right| = 0.2885\,\mathrm{THz}$. A conical horn antenna with a gain of 26 dBi radiates the QPSK-modulated THz carrier into free-space. A plano-convex THz lens made from polytetrafluoroethylene (PTFE) collimates the radiated beam.

The THz receiver as shown in Fig 2(b) directly transfers the THz data signal onto an optical carrier without prior down-conversion. The laser power at a frequency $f_{\mathrm{Rx,LO}} = 194.57\,\mathrm{THz}$ is amplified by an erbium doped fiber amplifier (EDFA) and is launched into the POH MZM through an on-chip grating coupler. The plasmonic modulator has a length *L* = 20 µm and a $U_\pi L$ product of 240 V µm, resulting in a figure of merit $n_{\mathrm{EO}}^3 r_{33} = 330\,\mathrm{pm/V}$. The QPSK modulated THz wave from the transmitter is received by a combination of lens and conical horn antenna that is similar to the one used at the transmitter. In order to compensate the free-space loss of the THz signal, a cascade of two millimeter-wave monolithic integrated circuit (MMIC) amplifiers with a total gain of 41 dB and a saturation output power of 4 dBm is employed. The amplifiers use state-of-the-art metamorphic high electron mobility transistors[11] (mHEMT). The THz power required to drive the plasmonic modulator can be reduced by optimizing the poling procedure and using materials with higher EO response, for which a figure of merit as large[12] as $n_{\mathrm{EO}}^3 r_{33} = 2300\,\mathrm{pm/V}$ has been demonstrated in a silicon-organic hybrid (SOH) MZM. The received THz signal is amplified in two stages – first by an H-band low-noise amplifier (LNA, 26 dB gain, 9 dB noise figure, −30 dBm maximum input power) and then by an H-band medium-power amplifier (MPA, 15 dB gain, saturation output power +4 dBm) – before driving the POH MZM through a THz GSG probe (GGB picoprobe Model 325B). The intensity-modulated output of the POH MZM is a T/O-converted signal with modulation sidebands centered around the optical carrier $f_{\mathrm{Rx,LO}}$. One of the modulation sidebands $(f_{\mathrm{Rx,LO}} \pm f_{\mathrm{Tx,THz}})$ is selected with a band-pass filter and is amplified to an optical power of 1 dBm before analyzing the signal quality with a coherent receiver (Agilent optical modulation analyzer N4391A, OMA). The signal received by the OMA is post-processed and equalized to evaluate the bit error ratio (BER).

Results and Discussion

An exemplary spectrum of the optical signal feeding the UTC-PD is shown in Fig. 2(c). Here, a 15 GBd QPSK data stream was used to modulate a 193.3°THz carrier, which is photomixed with a CW laser tone at 193.0115°THz, thereby transferring the signal to a carrier at 0.2885 THz. Fig. 2(d) shows the filtered lower sideband of the T/O converted intensity modulated optical signal after the POH MZM. The measured BER of the T/O-converted signal for different symbol rates of the QPSK data is shown in Fig. 2(e). The BER is below the threshold of forward-error correction (FEC) with a

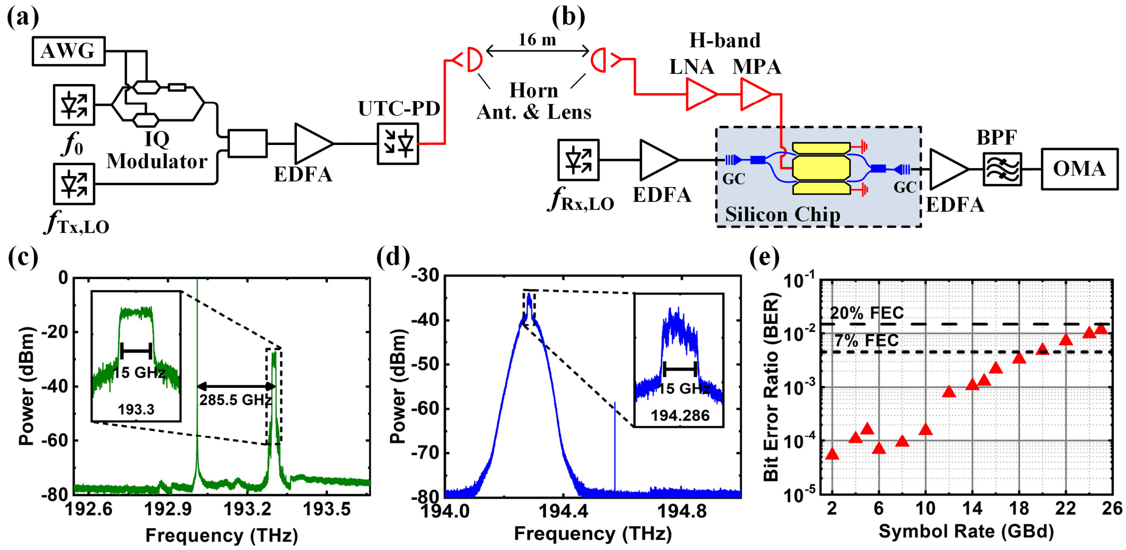

Fig. 2: Demonstration of fiber-wireless-fiber link. (a) THz transmitter setup for O/T conversion: An arbitrary-waveform generator (AWG) is used to modulate QPSK data on an optical carrier at f_0. The signal is then is superimposed with an unmodulated optical carrier at $f_{\mathrm{Tx,LO}}$, amplified and photomixed in a uni-travelling-carrier photodiode (UTC-PD) to generate a QPSK signal on a THz carrier. A horn antenna attached to the UTC-PD radiates the signal into free-space. A PTFE lens collimates the beam. (b) THz receiver setup for T/O conversion: Light from a laser at a frequency $f_{\mathrm{Rx,LO}}$ is amplified with an EDFA and coupled to a POH MZM on a silicon chip through an on-chip grating coupler (GC). The THz data signal received by a PTFE lens and a horn antenna is amplified by two H-band amplifiers (low-noise amplifier, LNA and medium-power amplifier, MPA) to drive the POH MZM for T/O conversion. The intensity-modulated signal generated by the POH MZM is amplified, filtered (band pass filter, BPF) to supress the carrier and one of the modulation sidebands, and analysed in an optical modulation analyser (OMA). (c) Optical spectrum carrying 15 GBd QPSK data (inset) at 193.3 THz and a detuned CW tone for feeding the UTC-PD to generate a THz carrier at 0.2885 THz. (d) Filtered spectrum of 15 GBd QPSK signal (inset) up-converted to 194.286 THz by the POH MZM. The drop in the power spectrum for the T/O-converted lower sideband at higher frequencies stems from the frequency-dependent gain of the THz amplifiers. (e) Measured bit error ratio (BER) of the T/O-converted signal for different symbol rates of QPSK data.

7 % overhead for symbol rates up to 18 GBd (line rate of 36 Gbit/s). For the 25 GBd QPSK signal with a line rate of 50 Gbit/s, we obtain a BER of 1.1×10^{-2} which is below the threshold for soft-decision FEC with 20 % overhead.

Summary

We demonstrate for the first time a seamless integration of a 0.2885 THz wireless link into a fiber-optic network. We exploit optical-to-THz conversion at the transmitter and direct THz-to-optical conversion at the receiver using an ultra-broadband plasmonic modulator. We demonstrate the viability of the concept by transmitting QPSK data signals with line rates up to 50 Gbit/s over a distance of 16 m.

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References

[1] "Cisco Visual Networking Index: Forecast and Methodology, 2016-2021", *White Paper* (2017).
[2] ITU-R Rec. P.676-11, "*Attenuation by atmospheric gases*", (2016).
[3] Nagatsuma, T. et. al., "Advances in terahertz communications accelerated by photonics", *Nature Photon.* **10,** 371–379 (2016).
[4] Koenig, S. *et al.* "Wireless sub-THz communication system with high data rate". *Nature Photon.* **7,** (2013).
[5] Melikyan, A. *et al., "*High-speed plasmonic phase modulators. *Nature Photon.* **8,** 229–233 (2014).
[6] Haffner, C. *et al., "*All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale", *Nature. Photon.* **9,** 525–528 (2015).
[7] Melikyan, A. *et al.* "Plasmonic-organic hybrid (POH) modulators for OOK and BPSK signaling at 40 Gbit/s" *Optics Express* **23,** 9938 (2015).
[8] Koos, C. *et al.* "Silicon-Organic Hybrid (SOH) and Plasmonic Organic Hybrid (POH) Integration" *J. Lightwave Technology.* **34,** 256–268 (2016).
[9] Ummethala, S et.al., "Terahertz-to-Optical Conversion Using a Plasmonic Modulator", Proc. CLEO, STu3D.4 (2018)
[10] Ito, H. et. al., "Photonic millimetre- and sub-millimetre-wave generation using J-band rectangular- waveguide-output uni-travelling-carrier photodiode module", *Electron. Lett.* **42,** 1424–1425 (2006).
[11] Tessmann, A. *et al., "*High-gain submillimeter-wave mHEMT amplifier MMICs", *IEEE MTT-S Int. Microw. Symp. Dig.* 53–56 (2010).
[12] Kieninger, C et al., " Ultra-high in-device electro-optic figure of merit n^3r_{33} = 2300 pm/V demonstrated in a silicon-organic hybrid (SOH) modulator", arXiv: 1709.06338 (2018).