Plasmonic Modulators for Future Highest-Speed Free Space Optical Communications

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Abstract: Plasmonic modulators have been assessed for operation up to 200 GBaud in a turbulent 53 km free-space-optical link. They are shown to withstand space radiation and large temperature ranges making them ideal for space applications. © 2022 The Author(s)

1. Introduction

Optical communication systems have played an indispensable role in terrestrial data communication for the past 30 years. Free-space-optical (FSO) communication links have the potential to play a similar role for earth-satellite and inter-satellite communication [1-3]. FSO links are unique as they are not limited by dispersion nor suffer from the nonlinear Shannon limit. So, FSO are almost ideal for operation at highest speed – if the respective transmitter would neither consume too much power nor too much footprint (some of the scarcest resources in space).

Highest single carrier symbol rate demonstrations include an 800 Gbit/s link over a distance of 42 m using PCS-64 QAM [2]. Similarly [4] has demonstrated for the first time a bit rate of 1 Tbit/s over a distance of 3 m employing a DP-100 GBd PCS-64 QAM signal. On the other hand, some demonstrations over longer distances fell short in high single carrier symbol rates. 40 on-off keying channels were used in a WDM scheme together with a fine-steering mirror to achieve 1.72 Tbit/s over a distance of 10.45 km [5]. The same link was increased to a throughput of 13.16 Tbit/s by using 54 channels each transmitting a DP-34GBd 16 QAM signal [6]. So, current experiments either show high-speed over short distances or low-speed WDM links over long distances. However, highest single carrier symbol rate demonstrations over realistic distances are needed to verify that reliable high-speed transmission in an earth-satellite link with turbulent atmospheric conditions is possible at all. Recently and for the first time we demonstrated a Tbit/s single carrier link over a distance of multiple kilometers [7]. Yet, also this system was bandwidth limited by the optical modulator, see the pink plot in Fig. 1(d). Lately, plasmonic modulators have emerged. They offer bandwidths in excess of 500 GHz [8], most compact footprints and power consumption in the aJ/bit [9] and offer stable operation across a wide temperature range from 4 K up to 353 K [10, 11].

In this paper, we demonstrate reliable 160 GBd transmission across a turbulent 53 km free-space link by means of plasmonic modulators. The absence of a nonlinear-Shannon limit favors multilevel modulation formats such as, DP-4ASK by which 424 Gbit/s transmission is shown. Further, we show that it can withstand space radiation with only minor degradation. In combination with the compact footprint, the low power consumption, high bandwidth, and stable operation across a wide temperature range, the plasmonic modulator is a promising candidate for usage in future optical satellite links.

2. Outdoor Demonstration Setup

Fig. 1(a) shows the experimental setup with (c) showing a map of the outdoor demonstration locations. The demonstration was performed over a 53 km link spanning from the Jungfraujoch High-Altitude Research Station (HFSJG) at 3700 m above sea-level to the Zimmerwald Observatory (ZO) at 895 m altitude. As the link stays within the first turbulent atmospheric layer, this constitutes a worst-case scenario for earth-satellite links [12].

A 256 GSa/s arbitrary waveform generator (AWG) with a 65 GHz driver-amplifier (DA) is used to generate digital pulse-amplitude-modulated (PAM) signals with a square-root-raised cosine pulse shape in the Tx-DSP. This signal is fed to a plasmonic modulator, shown in Fig. 1(b) and used to generated 2, 4 and 8 ASK symbols. The packaged modulator offers a bandwidth of >110 GHz as shown in the frequency response in Fig. 1(d). The

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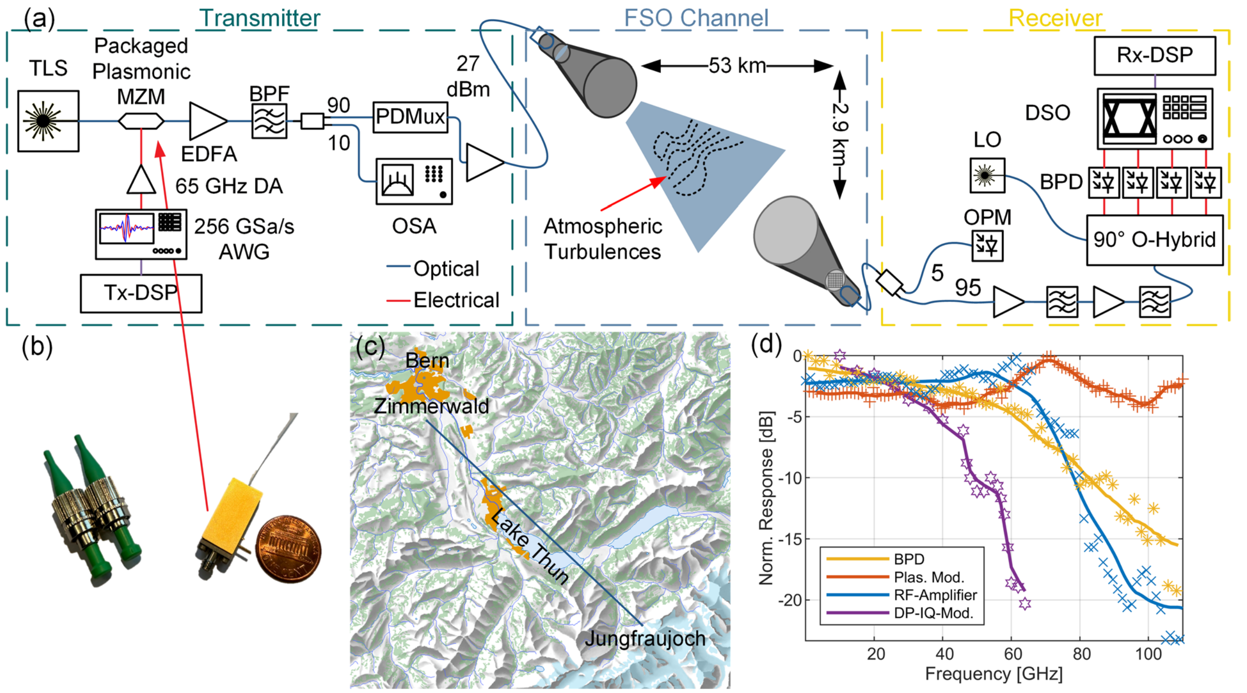

Fig. 1. FSO link with plasmonic modulator, landscape, and bandwidth limitations in the system. (a) Experimental setup of the outdoor demonstration indicating the FS link distance. (b) Picture of the used modulator and a size comparison to a US 1 Cent coin. (c) Map of the localities in the outdoor demonstration ©swisstopo. (d) Measured frequency responses of the used balanced photodiodes (BPD), RF-amplifier and packaged plasmonic modulator (Plas. Mod.). Solid lines represent a moving average of the measured data, indicated by the markers. For comparison the DP-IQ-modulator (DP-IQ-Mod.) which was used in [7] is shown.

modulator is operated by a 1550 nm tunable laser source and is biased around the Null point to generate PAM (or bipolar amplitude-shift-keying (ASK)) signals. After the modulation, the signal is amplified by an erbium doped fiber amplifier (EDFA). A dual-polarized signal is generated using a polarization division multiplexer (PDMux). The signal is then amplified to 27 dBm for free-space transmission through a space terminal with a sub-aperture of 4.2 cm. After propagation through 53 km of atmosphere, the signal is received at the ZO by the FEEDELIO optical ground station consisting of a telescope with an aperture of 35 cm, an adaptive optics system (AOS) consisting of a deformable mirror and a wavefront sensor composed of an 8x8 array [13]. The incoming optical beam is then directly coupled into a single mode fiber, more details can be found in [12]. 95 % of the signal is pre-amplified in a LNA prior to going through a second amplification stage, the remaining 5 % are used to monitor the optical power of the coupled flux. Afterwards, the signal is fed to a DP-90° hybrid mixer whose output is sent to four 70 GHz balanced photodetectors (BPDs) and digitized by a 256 GSa/s digital storage oscilloscope (DSO) with an analog bandwidth of 110 GHz. The channel is assumed to be constant over the acquisition time of 15.62 µs. The recorded waveform of the DSO is then processed by an offline DSP consisting of matched filtering, timing recovery, a 2x2 polarization demultiplexer, and a carrier recovery followed by a linear and non-linear equalizer.

3. Results

Fig. 2(a) shows the line- and net-data rates for signals with up to 200 GBd. Solid lines represent net-data rates while dashed lines correspond to line-rates. Net-data rates are calculated by multiplying the generalized mutual information values (GMI) with the corresponding symbol rates. A normalized GMI (NGMI) threshold of 25% as needed to perform error correction with the concatenated SD-HD-FEC [14] was used. Here, NGMI is used as a performance indicator for the error proneness of a system as it indicates how much information can be decoded independent of the modulation format. The highest net-data rate below the stated FEC threshold was achieved with the 128 GBd DP-4ASK signal offering a net-data rate of 424 Gbit/s, point 1 in Fig. 2. The corresponding spectrum as well as the probability density function of the symbols after offline DSP can be seen in Fig. 3(a) and (b). Further, the 64 GBd DP 8ASK offers a net data rate of 338 Gbit/s, point 2 in Fig. 2, with the 160 GBd DP-2ASK reaching a net-data rate of 276 Gbit/s, point 3 in Fig. 2. Due to the bandwidth limitations in the system the 200 GBd DP-2ASK only reached a net-data rate of 263 Gbit/s.

To assess the suitability of plasmonic modulators for space applications, total ionization dose (TID) radiation hardness tests with of up to 50 krad (Si) were performed on unpackaged, unpassivated devices. These dose values are representative for typical LEO and GEO orbits, as investigated in satellite mission simulations with 10-year

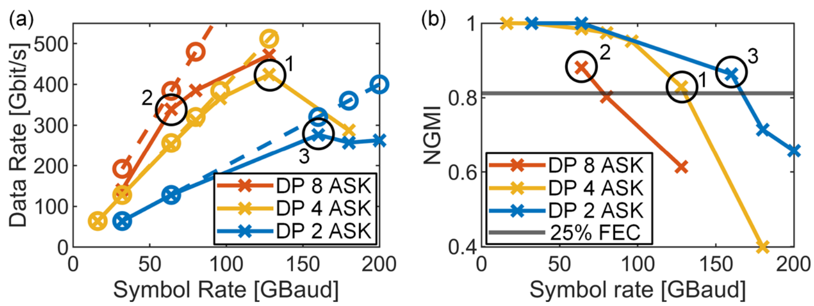

Fig. 2 Data rates as well as a NGMI is shown. (a) Showing the achieved line rates (dashed lines) as well as net-data-rates (solid lines). (b) shows the corresponding NGMI values with a 25% SD-FEC threshold visualized as well. In both plots the points with highest throughput for the respective modulation format are highlighted.

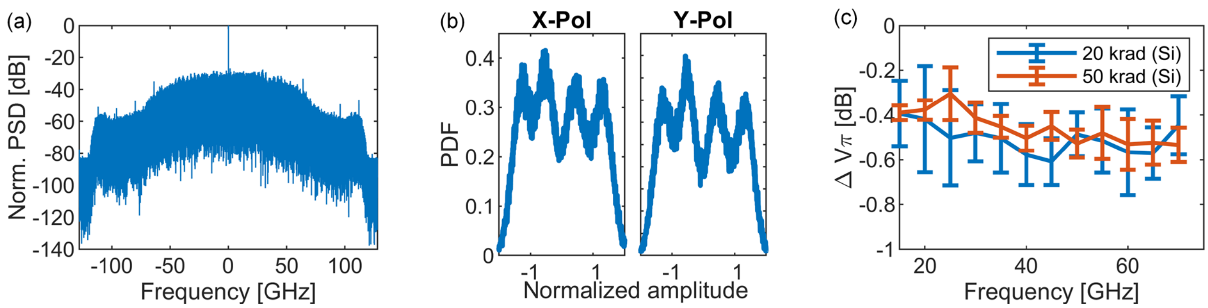

Fig. 3 Achieved spectrum, PDF 128 of the GBd DP-4ASK signal as well as the obtained results from radiation testing. (a) Digital electrical spectrum at the input to Rx DSP with an analog signal bandwidth of 64 GHz. (b) The PDF of the normalized amplitude vs occurrence, one can distinguish well between the 4 amplitude values. (c) Results of radiation tests performed with a set of six plasmonic modulators. A moderate average degradation of 0.5 dB has been found on the V_π for radiation powers that correspond to a 10-year LEO space exposure. Error bars are indicating the variance across the devices.

duration and Al shielding thicknesses below 5 mm using the AE-8, AP-8 and SHIELDOSE-2 models [15, 16] in SPENVIS [17]. Dose-independent, low changes in the order of 0.5 dB V_π (in line with results from [18]) were observed over the considered bandwidth of 70 GHz, see Fig. 3(c). This value represents a maximum degradation due to space radiation as the samples were not passivated and part of the effect might be due to ambient exposure.

4. Conclusion

FSO channels can be operated at highest bit rates. The atmospheric turbulences lead to attenuation that can be overcome with adaptive optics – but otherwise there is no obvious limit to higher symbol rates. Link limitations -if at all - are due to bandwidth restrictions from equipment that may be overcome with novel high-speed devices.

In this work, for the first time FSO signals reaching the 200 GBd mark have been demonstrated by employing, high bandwidth, small footprint, radiation resistant and thermally stable plasmonic modulators. In terms of turbulence the link represents a worst-case earth to satellite scenario spanning a distance of 53 km with an elevation difference of 2900 m. Highest single carrier symbol rates of up to 160 GBd and net-data-rates of up to 424 Gbit/s utilizing a 128 GBd DP-4ASK signal were accomplished, staying below the FEC limit for 25% overhead. In the future even higher data rates may be enabled by using plasmonic IQ modulators.

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