Mid-IR Free-Space Optical Communications Using WDM and OAM

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Abstract *This paper will highlight free-space optical (FSO) communications in the mid-infrared (mid-IR) using wavelength division multiplexing (WDM) and orbital angular momentum (OAM)-based mode division multiplexing (MDM). Mid-IR issues to be discussed include: (a) methods to modulate and detect, and (b) WDM and OAM-based MDM techniques. ©2023*

Introduction

Free-space optical communications has attracted much interest due to the potentially higher data capacity and lower probability of detection by eavesdroppers when compared to radio-based systems [1,2]. Moreover, there is growing interest in mid-IR FSO communications [3] since the mid-IR has several transmission windows that potentially provide a relatively lower atmospheric attenuation and beam distortion when compared to the C-band [4]. There have been various reports of single-channel mid-IR FSO communication systems employing transmitters/receivers that: (a) "natively" generate and detect light in the mid-IR (*e.g.*, quantum cascade lasers) [5-8], and (b) use high-bandwidth C-band generation/detection devices and wavelength up-and-down conversion for transmission [9-11].

To increase the total data capacity of optical communication systems, multiplexing techniques have been utilized. Multiple independent data channels can be multiplexed using different domains of the optical waves and transmitted simultaneously through the medium. Specifically, wavelength division multiplexing (WDM), where each channel occupies a different wavelength, has been widely deployed in the C-band [12-14].

Another capacity-increasing multiplexing technique is space-division-multiplexing (SDM) [15]. One subset of SDM is mode division multiplexing (MDM), in which multiple beams are simultaneously transmitted each located on an orthogonal spatial mode and carrying an independent data channel [15]. For example, one modal basis set is orbital angular momentum (OAM) modes, which is a subset of Laguerre-Gaussian modes [16]. A beam that carries OAM (i) has a phasefront that "twists" in a helical fashion as it propagates, (ii) has an intensity null at the beam center, and (iii) can be characterized by the OAM order ℓ, which is the number of 2π phase shifts in the azimuthal direction. In the C-band, there have been demonstrations of: (a) single-wavelength MDM FSO links [12,16], and (b) a combination of WDM and OAM-based MDM FSO links [12].

A potentially important issue is the use of multiplexing techniques for increasing the total capacity of mid-IR communication links [17].

The concept of FSO communication system in the mid-IR is shown in Fig. 1. Multiple data channels are carried by beams with different mid-IR wavelengths and orthogonal OAM modes. These channels are multiplexed and transmitted through free space. The WDM mid-IR channels are generated in the C-band and wavelength converted to the mid-IR. The mid-IR Gaussian beams are converted to mid-IR OAM beams by passing them through spiral phase plates (SPPs). A total capacity of 300 Gbit/s for 6 WDM-OAM data channels is shown [17].

In this paper, we review FSO communications in the mid-IR using WDM and MDM [18]. The paper outline is as follows: (a) introduction of the effects in the mid-IR FSO communication links, (b) various methods of modulating and detecting signals on mid-IR beams, (c) WDM in the mid-IR, (d) generation and detection of mid-IR OAM beams, and (e) system performance using both wavelength- and mode-multiplexing techniques.

Modulation and Detection of Data

There are generally two ways to modulate and detect data on mid-IR beams for single-channel mid-IR FSO communication systems, as shown in Fig. 2. One method to achieve mid-IR FSO communications is to use "native" mid-IR devices. In such systems, the data signal is modulated onto the mid-IR beams by using direct modulated mid-IR lasers or mid-IR modulators. At the receiver, the data-carrying mid-IR beams are detected using PDs covering the mid-IR wavelength region.

One could also use wavelength conversion for enabling the transmission of the data-carrying mid-IR beams. In such systems, the data signal is modulated on C-band wavelengths for which high-speed modulators are widely available. Subsequently, the data-carrying beam is wavelength converted to the mid-IR region through optical nonlinear processes for transmission. At the receiver, the data-carrying mid-IR beams are wavelength converted back to the C-band. A typical nonlinear device for wavelength conversion is a periodically poled lithium niobate (PPLN) waveguide [9-11].

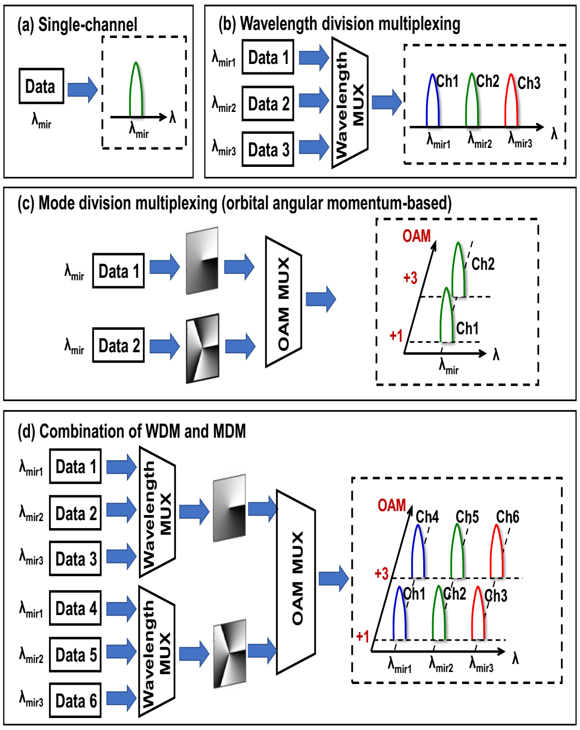

Fig. 1: Concept of a mid-IR free-space optical communication system with (a) single channel transmission, (b) wavelength division multiplexing (WDM), (c) mode division multiplexing (MDM), and (d) a combination of WDM and MDM.

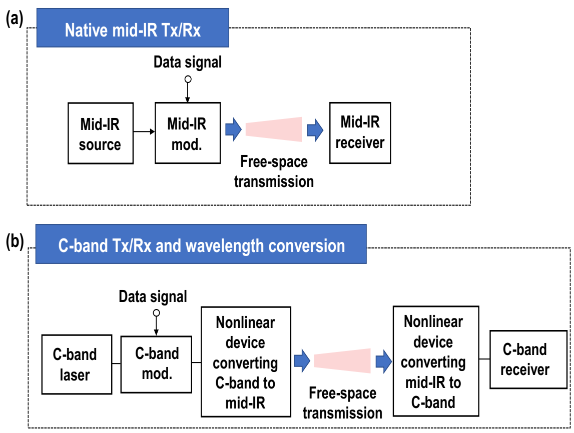

Fig. 2: Approaches for modulation and detection of a mid-IR beam: (a) using "native" mid-IR transmitters/receivers; and (b) using C-band transmitters/receivers and nonlinear wavelength conversion between the C-band and mid-IR.

WDM in the Mid-IR

WDM in the mid-IR region can be achieved by wavelength conversion between the C-band and the mid-IR region [17] through difference-frequency generation (DFG). In DFG, the WDM signals in the C-band that are all in the phase-matching bandwidth of the PPLN waveguide can be simultaneously wavelength converted by the PPLN. Figure 3(a) shows a spectrum of three WDM channels at ~3.4-μm wavelength generated by wavelength conversion in a PPLN [17]. Three mid-IR wavelengths with 27.5-GHz channel spacing are multiplexed, each carrying a 25 Gbaud quadrature-phase-shift-keyed (QPSK) signal. The spectral shapes are not completely resolved by the optical spectrum analyzer (OSA) for the mid-IR, as the OSA has an ~1-nm resolution, which tends to be greater than the spectral bandwidth of the data channels themselves.

Three 25 Gbaud QPSK signals at different wavelengths are multiplexed and the total capacity is 150 Gbit/s. As shown in Fig. 3(b), the bit-error-rates (BERs) as a function of the optical signal-to-noise ratio (OSNR) are measured.

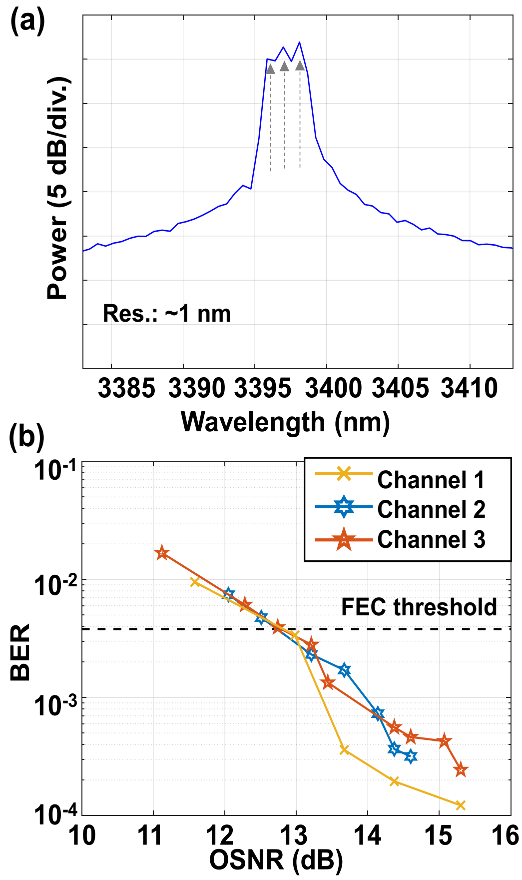

Fig. 3: (a) Spectrum of generated mid-IR WDM signals with a resolution of ~1 nm. Arrows indicate the three mid-IR WDM channels. (b) BER as a function of OSNR for all the three multiplexed channels of the mid-IR WDM FSO communication system [17].

OAM-based MDM in the Mid-IR

OAM-based MDM mid-IR FSO communication systems have been demonstrated by using SPPs to generate and detect OAM beams [19]. In this demonstration, SPPs that have a helical surface were used to generate mid-IR OAM beams by passing mid-IR Gaussian beams through them.

Figure 4(a) shows the beam profiles of the generated mid-IR OAM beams [17]. On the top left are the intensity profiles of the OAM +1 and +3 beams. The intensity profiles have a ring-like shape and have larger beam size for higher OAM orders. On the bottom left are interferograms of the corresponding OAM beams with a coherent Gaussian beam. The interferograms show twisted arms and the number of arms indicates the order of the OAM beam. On the top right is an intensity profile of two multiplexed data-carrying OAM +1 and +3 beams at the transmitter. On the bottom right is the intensity profile when passing the multiplexed two OAM beams through an SPP with the order of -3 at the receiver. This intensity profile shows that the OAM +3 beam is down-converted to a Gaussian-like beam while the OAM +1 beam still has a ring-like shape.

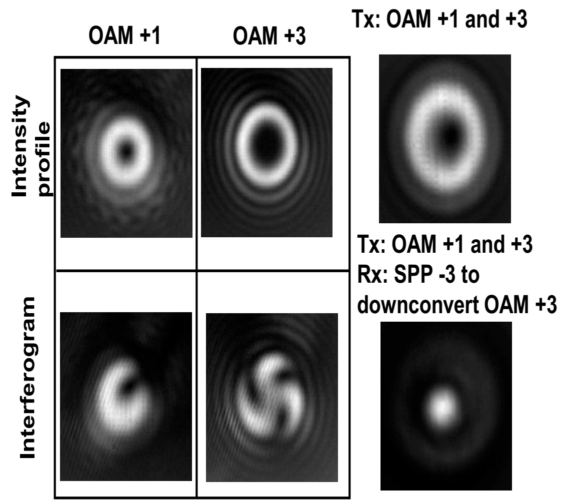

Fig. 4: Left: Intensity profiles and interferograms with a Gaussian beam of the mid-IR orbital angular momentum (OAM) beams. Top right: Intensity profile of the multiplexed data-carrying OAM +1 and +3 mid-IR beams. Bottom right: Intensity profile of the multiplexed OAM beams passing through an SPP with the order of −3 [17].

Combining Both Multiplexing Techniques

A mid-IR FSO communication system combining both WDM and OAM-based MDM has been demonstrated [17]. In this demonstration, two OAM modes each containing three mid-IR wavelengths were multiplexed, resulting in six channels in total. With each channel carrying a 25 Gbaud QPSK signal, a total gross capacity of 300 Gbit/s was achieved.

The BER-OSNR performance of all the six multiplexed channels is shown in Fig. 5, with all the channels achieving a below forward-error-correction (FEC) limited BER.

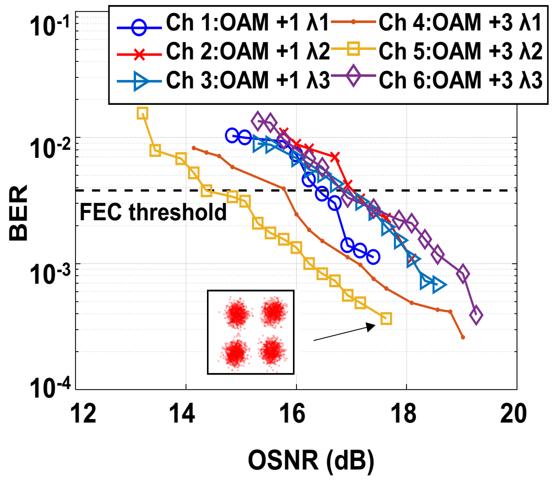

Fig. 5: BER of all the multiplexed six channels as a function of OSNR of the mid-IR FSO communication system multiplexing two OAM modes, each with three multiplexed mid-IR wavelengths [17].

Conclusions

In summary, this paper discussed mid-IR FSO communication systems using WDM, MDM, and a combination of WDM and MDM. We described the effects of mid-IR wavelengths in the FSO links and discussed the methods to modulate and detect data on the mid-IR wavelengths.

Acknowledgements

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