All-Optical THz-band Frequency Multiplexing on A Single Optical Carrier Using Fiber Cross-Phase Modulation

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Abstract: We developed an ultra-broadband all-optical frequency multiplexing technique on a single optical carrier using cross-phase modulation in nonlinear fibers, and demonstrated sequentially multiplex of multi-channel Gigabit ASK/DPSK signals on THz-band.
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1. Introduction

For large capacity and high spectral efficiency transmission on a single wavelength optical carrier, data multiplexing technologies as well as advanced modulation technologies have been investigated, including multi-level PSK, QAM, OFDM, and others [1]. Also in the field of wireless communication, intense research has been done to develop data transmission using carrier frequencies above 100 GHz. As an example of optical/wireless interface, radio-over-fiber (ROF) technology has been investigated with ultra-wide band optical devices to effectively convert the base-band data signal to over 100 GHz band RF signal [2,3]. Making an optical network flexible so that arbitrary information can be freely/directly accessed and communicated across different networks requires an ultra-broadband data multiplexing technology covering THz-class bandwidth.

Cross-phase modulation (XPM) in fiber can be used to linearly modulate the phase of an optical carrier well over the THz frequency range [4]. If, for example, an amplitude-modulated signal is launched into an optical fiber, the phase of the optical carrier is shifted in proportion to the intensity of the signal wave. Therefore, the fiber can be used as an optical phase modulator, to construct ultra-broadband data multiplexing networks which can provide a vast amount of data signals 'at any point' along the transmission line.

In this paper we present an optical data multiplexing system. We developed based on the described modulation concept, in which up-converted data signals by optical frequency detuned optical beat are multiplexed sequentially on a single wavelength optical carrier by XPM in a fiber. The system was experimentally demonstrated using highly nonlinear fibers (HNLFs) by successive 4-stage multiplexing in a transmission line. Terahertz range multiplexing, of 16-channels, each carrying 1 Gb/s ASK and DPSK signals, was successfully demonstrated with error free transmission through a standard fiber link.

2. RF modulation by fiber XPM

XPM in optical fiber is utilized to modulate the phase of an optical carrier. This scheme has the potential for ultra-high-speed and wide bandwidth response. It has low loss compared with conventional opto-electronic phase modulators (LN-modulator, etc.) and high linearity compared to XPM in semiconductor optical amplifiers (SOA) by optical signals. We propose the XPM modulation to realize an optical multiplexer (OM) for data signals as shown in Fig. 1. The proposed multiplexer consists of an optical coupler that combines a control signal and a carrier signal, an optical nonlinear fiber, and a filter that rejects the control signal. The phase of the carrier signal is shifted in proportion to the intensity of the control signal.

In the proposed multiplexing scheme, the optical phase of the carrier signal is all-optically modulated by a control signal. An optical beat signal with frequency separation of $f = |\nu_1 - \nu_0|$ is adopted as frequency up-converted control signal to demonstrate the ultra wideband operation. Multipoint multiplexing can be achieved in the optical

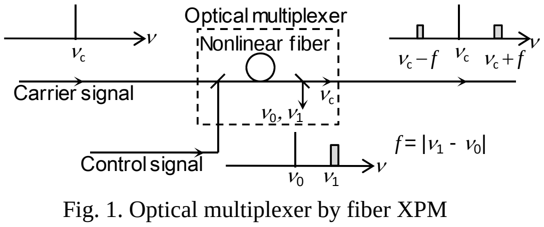


Fig. 1. Optical multiplexer by fiber XPM

frequency domain by cascading several OMs. The proposed OM can be expected to utilize its wide bandwidth to multiplex a large number of data channels.

3. Experiment

We tested the effect of the proposed OM using the setup shown in Fig. 2. The carrier signal was a continuous wave (CW) at a wavelength of λ_c = 1539.8 nm (ν_c = 194.7 THz) with an input power of P_C = +11 dBm. The control signal was generated with beat waves by combining a CW signal and the data signals with matched state of polarization (SOP) at an optical terminal (OT-j). Four channels of ASK or DPSK data signals were modulated at 1-Gb/s (PN: 2^{31}-1) by a LN intensity or phase modulator. The data signals had a wavelength of 1556.5 nm (192.6 THz) with 5-GHz spacing and the center frequency of the control signal, ν_{j0} (λ_{j0}), was tuned to obtain the up-conversion frequency of k-th channel at $f_{jk} = \nu_{jk} - \nu_{j0}$. The control signal was combined with the carrier signal and then launched into a 500-m long highly-nonlinear fiber (HNLF). The SOP of the control signal was controlled to match the carrier signal. The HNLF had a nonlinear coefficient of $\gamma \sim 20\ \mathrm{W^{-1}km^{-1}}$ and a zero-dispersion wavelength of $\lambda_0 \sim$ 1550 nm. The wavelengths of the carrier signal and the control signal were symmetrically allocated with respect to λ_0 to achieve better phase matching. The couplers before and after the HNLF were WDM couplers, which did not limit the signal bandwidth. The input power of the control signal was set to P_{Sj} = 15 dBm. In the first step we measured the frequency dependency of the modulation efficiency, which is defined as the optical power ratio of the signal component to the main carrier. A flat response up to 1 THz was obtained as shown in Fig. 3. The observed decay of efficiency is mainly due to a residual phase mismatch between carrier and control signal. Considering the ultra-broad bandwidth of XPM in a fiber [4], well over THz bandwidth can be expected by further optimizing the wavelength arrangement.

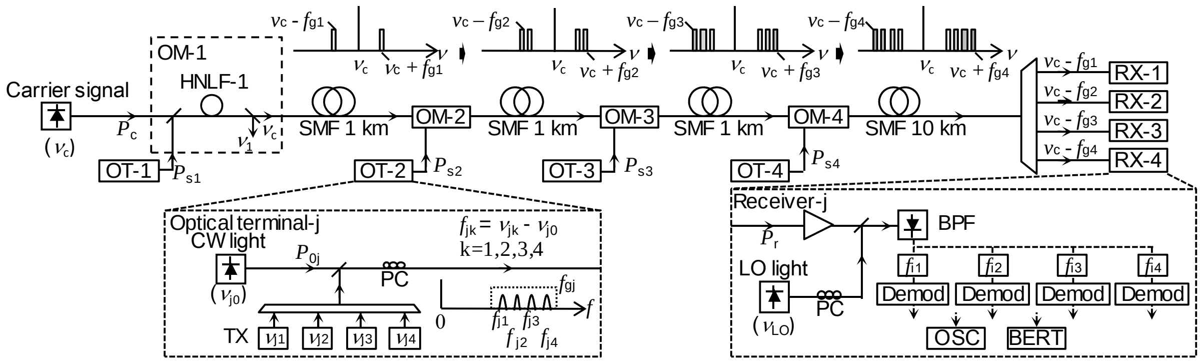


Fig. 2. Experimental setup of 4-stage multiplexing

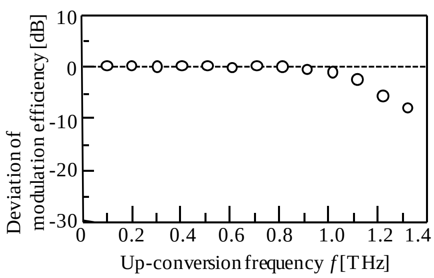


Fig. 3. Frequency dependence of modulation efficiency.

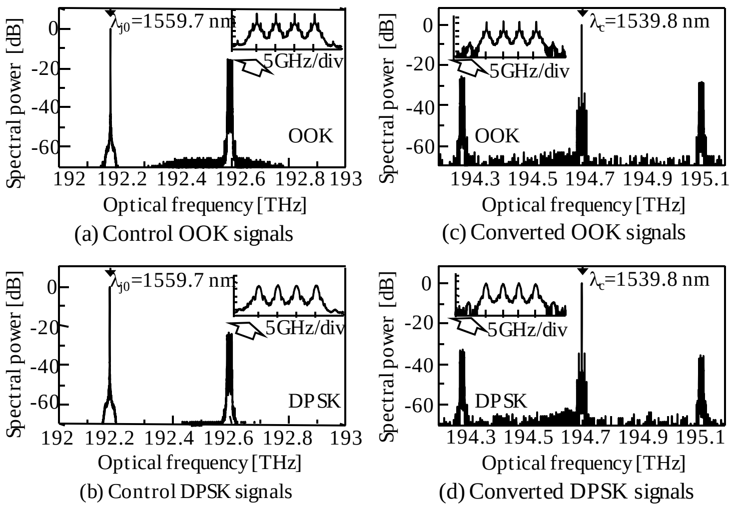
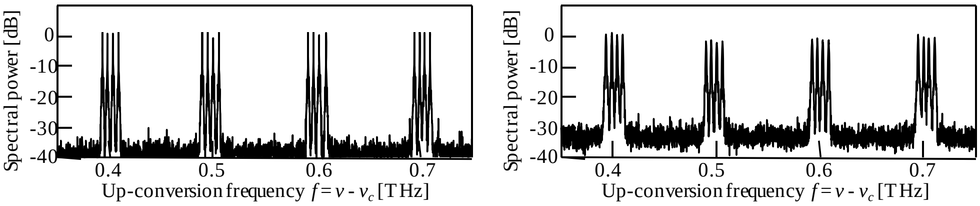
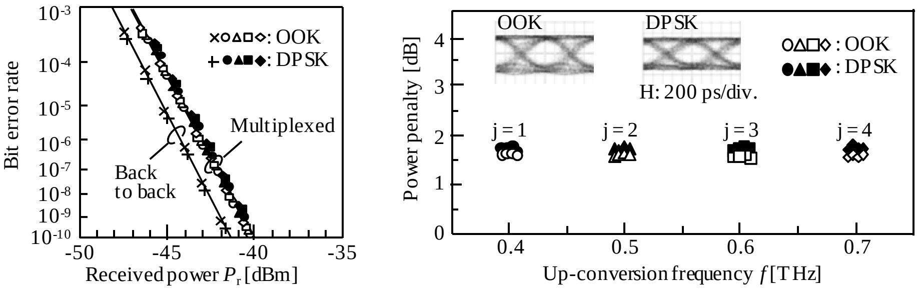


Fig. 4. Optical spectrum of the input control signal and the output carrier signal of the single stage configuration. Inset: enlarged spectra of the four channels frequency multiplexed data signals



(a) OOK signals (b) DPSK signals

Fig. 5. Optical spectrum of 16-ch multiplexed signals.



(a) Bit error rate characteristics (b) Power penalty of all channels. Insets are demodulated waveform of typical channel

Fig. 6. Bit error rate characteristics (a), and the measured power penalty (b), after 10-km transmission.

As shown in Fig. 2, four OMs were put in every 1 km standard single-mode fiber (SMF). At each OM, the control signal with up-conversion frequencies around 0.4, 0.5, 0.6, and 0.7 THz were inserted, respectively. The frequency multiplexed carrier signal was transmitted through the 10-km long SMF.

At the receiver the signal combs were demultiplexed by 100-GHz spacing arrayed waveguide grating and the four signals per comb were frequency down-converted by a single local LD, heterodyne-detected by a photo diode, and filtered by electrical band-pass filters (BPFs (f_{ik})) with 2-GHz bandwidth. The intermediate frequency of four signals and the center frequency of the four BPFs were set to be the same as 10, 15, 20, and 25 GHz, respectively. Bit-error rates (BERs) and waveforms were measured after demodulation by an envelope detector for the OOK signal and a 1-bit delay demodulator for the DPSK signal [5]. We measured the modulation efficiency with OOK signals and DPSK signals by using an optical complex spectrum analyzer (AP2441A) with a 100 MHz resolution. Figure 4 shows the optical spectra of the control and carrier signal at the output of the first HNLF with the up-conversion frequency of 0.4 THz. Four channels of both the OOK signal and the DPSK signal were converted with the same efficiency as shown in insets of Fig. 4.

Figure 5 shows the optical spectra after the 4-stage multiplexing. 16-ch signals were converted with the same efficiency. BER characteristics of channels multiplexed at OM-1, 2, 3 and 4 after the transmission are shown in Fig. 6. The received power in Fig. 6 is the optical power of a measured single channel per comb. Error free operation was achieved for all the channels with a power penalty of < 1.8 dB. No distortion in the waveforms was observed after the multiplexing. The number of channels in our experiment was limited by the available equipments. The frequency multiplex over the whole THz-range could be achieved by this scheme.

4. Conclusions

We developed a frequency domain optical data multiplexing system in which data signals were all-optically multiplexed sequentially on a single wavelength optical carrier by XPM in nonlinear fibers. Using up-converted optical signals generated by optical beating at frequency over THz-band, we successfully demonstrated the frequency multiplexing of 16x1-Gb/s OOK/DPSK data signals on a single wavelength optical carrier by successive four-stage fiber-XPM for the first time.

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