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155 Mb/s–10 Gb/s combined FSK-IM/optical label-packet modulation signals 100 km transmission over standard single mode fiber using mid-span spectral inversion by four-wave mixing in an SOA*

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This paper introduces the mid-span spectral inversion by four-wave mixing in a commercially available semiconductor optical amplifier (SOA) with a length of about 1.5 mm to optical label switching network based on combined frequency shift keying (FSK)-intensiy modulation (IM)/optical label-packet modulation to overcome the dispersion limitation of fiber. The 155 Mb/s–10 Gb/s combined FSK/IM signal is experimentally transmitted over a 100 km standard single mode fiber. 10^{-10} and 10^{-9} BER (bit error ratio), or even better, is achieved for the FSK label and IM packet, respectively. The −19 dB power conversion efficiency is obtained for −1 nm wavelength detuning.

Keywords: optical label switching, mid-span spectral inversion, semiconductor optical amplifier
PACC: 4230Q

1. Introduction

The ever-increasing demand for bandwidth and flexibility for the Internet, which accommodates diverse services, such as voice-over-IP (VoIP), IP television (IPTV), etc., are driving the current transport networks based on Synchronous Digital Hierarchy (SDH) to migrate to an optical packet switching (OPS) network, which is capable of providing greater bandwidth efficiency, flexibility, and functionality, and also offering finer granularity.[1] Because OPS still requires technological breakthroughs such as optical memories and buffering subsystems, therefore, an intermediate technique for alleviating the migration to OPS is needed. Optical label switching is considered to be a suitable one which introduces label controlled routing and at the same time performing the switching of high-speed data packets transparently without opto-electrical-optical conversion. Focusing on the approaches of coding optical labels onto the packet, several techniques have been proposed so far.[1,2] Among them, one promising technique is the so-called combined modulation scheme, frequency-shift keying/intensity modulation (FSK/IM), where the information of the label and the packet are conveyed simultaneously by using a single optical carrier[1−4] through FSK and IM, respectively. When the pure IP packet reaches the OLS network, the edge nodes (ingress/egress) encapsulate or remove the corresponding label for the packet, while inside the OLS network, the packet undergoes all optical label swapping controlled by the optical label.

The FSK tone spacing is a key parameter in such a network, which is usually above 10 GHz in order to filter one tone of FSK for detecting. But that value is large enough and will introduce severe walk-off to high

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speed IP packet due to the dispersion of fiber used as a transmission medium. In order to solve this problem, dispersion compensation fiber (DCF) has been adopted so far in all reports as far as the authors know.[1,2]

In this paper, we introduce mid-span spectral inversion (MSSI) by four-wave mixing (FWM) in a commercially available SOA to OLS networks based on combined FSK/IM modulation to alleviate the impact of fiber dispersion, which has the advantages of small size, low cost, high energy efficiency, etc., compared with the DCF based case. In addition, the format effect at high speed which must be faced by SOA can also be solved by means of red or blue frequency shifts through the matched fiber grating,[5,6] and a 320 Gb/s proceeding rate was reported.[6] To validate our scheme, a 155 Mb/s–10 Gb/s combined FSK-IM/Optical label-packet modulation transmission experiment over 100 km standard single mode was carried out through mid-span spectral inversion by four-wave mixing in an SOA with length of about 1.5 mm.

2. Experimental setup

The experimental setup is shown in Fig.1. 155.52 Mb/s (STM-1- synchronous transport modules bit rate in SDH) nonreturn to zero (NRZ) code with pseudo-random binary sequences of $2^{15}-1$ length acting as a label directly drives a DFB laser with a fixed nominal wavelength of 1560.092 nm and biased above threshold to generate a frequency shifted keying (FSK) output spectrum with two tones due to the laser's frequency chirp. The 10 Gb/s NRZ code with PRBS of $2^{23}-1$ length acting as packet is added by a Mach–Zehnder modulator, thus generating a combined FSK/IM signal. The combined FSK/IM optical signal is amplified by an erbium doped fiber amplifier (EDFA) with noise figure of 6 dB before injecting into transmission link. The transmission link consists of four spools of standard single mode fiber made by Corning with loss of 0.19 dB/km, dispersion of -17 ps/(nm·km) and dispersion slope of 0.089 ps/(nm^2·km) at 1550 nm wavelength. The length of each spool is 25 km. A commercially available SOA with a length of about 1.5 mm is placed in the middle of the transmission link to execute spectrum inversion via four wave mixing (FWM). Before the SOA, the combined FSK/IM signal together with a continuous light from a pump laser with tunable wavelength and output power are amplified by an EDFA with a maximum of 27 dBm output optical power, then input to SOA. At the receiver end, the combined FSK/IM is first amplified by EDFA, then divided by a 50:50 coupler and sent to a FSK and IM receiver,

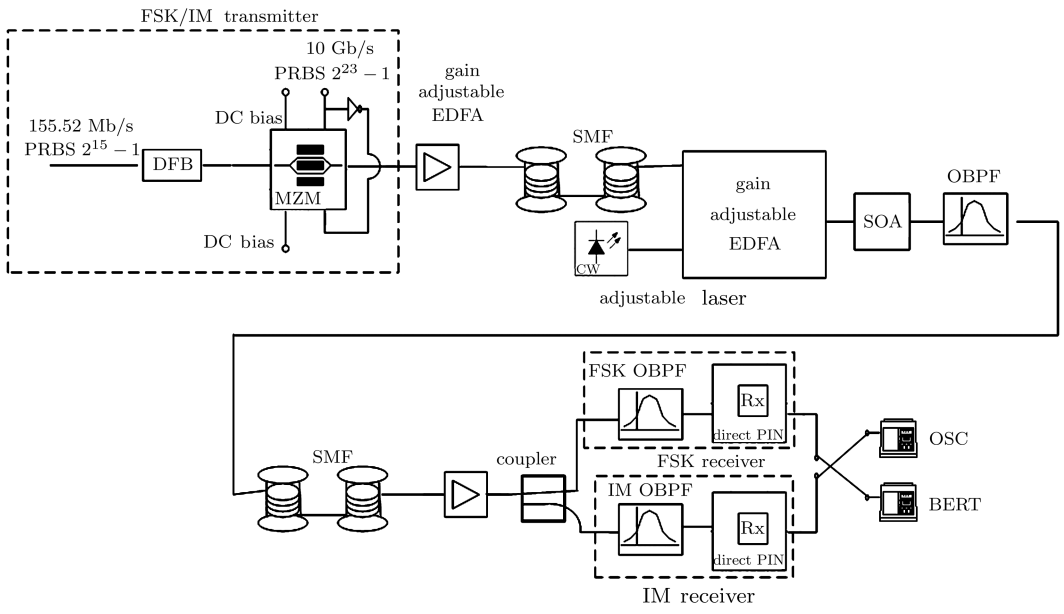


Fig.1. 155 Mb/s–10 Gb/s combined FSK-IM/Optical label-packet modulation signals 100 km transmission experimental setup.

respectively. In the front of the FSK receiver, a filter with tunable wavelength and pass bandwidth is adopted to select one of FSK tone. A wavelength tunable filter with 3 dB bandwidth of 0.4 nm is placed in the front of the IM receiver. Agilent Infiniium DCA 86100A wide-bandwidth oscilloscope and Agilent N4901B 13.5 Gb/s Serial BERT bit error code tester are used to measure eye diagram and bit error ratio (BER), respectively.

3. Experimental results and discussion

Figure 2 depicts the case where the pump wavelength is set at 1558.762 nm, which is also used to measure the BER and eye diagram of FSK and IM signals, respectively. The inset at the top-left corner of the figure shows the optical spectrum of the FSK label. The tone space of FSK signal is decided by the driving current, and 0.112 nm of tone space is adopted in our experiment. It can be seen that the intensity of FSK signal is simultaneously modulated with two unequal tones, which will degrade the IM packet quality. A balanced FSK spectrum is preferred. Improved generation schemes of FSK label with balanced spectrum via reshaping filter and electroabsorption modulator have been reported in our work[4] and Ref.[7], respectively. Our main object here is to validate the function of MSSI by FWM in an SOA, therefore, no balance measures are adopted. It should be noted that the quality degradation of the IM packet due to unbalanced tone of FSK is further deteriorated for down spectrum inversion as the FSK source spectrum depicted in Fig.2 is adopted, where the long wavelength tone is weaker. Such a case can be avoided if the FSK source spectrum can be adjusted.

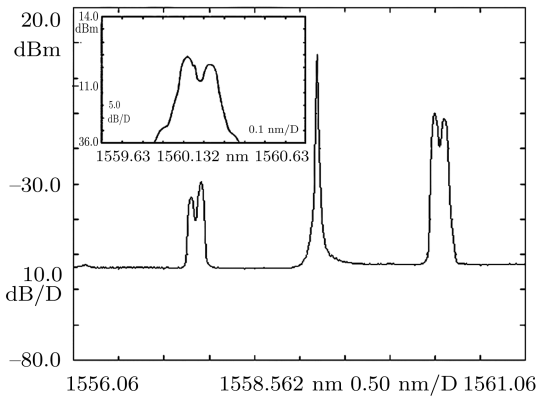


Fig.2. Output optical spectrum of SOA at the mid span of transmission link.

The BER of the IM packet versus the injected power to the IM receiver is plotted in Fig.3 when MSSI is utilized. Below 10^{-9} the BER can be achieved when the received optical power is higher than −9 dBm. The BER should be measured without MSSI so that a comparison can be done. However, it is unfortunate that the BER is high enough, and there is no sense in doing such a comparison. But we still show the eye diagram of IM packet without MSSI for −12 dBm of received optical power, which is inserted at the bottom-left corner in Fig.3. It can be seen that the eye almost disappears. This result is predictable due to dispersion introduced by the broad optical spectrum of the IM packet with more than 0.112 nm of 3 dB bandwidth for 10 Gb/s high speed data in 100 km SMF. Under the same received optical power, the eye diagram of the IM packet with MSSI is shown as an inset at the top-right corner of Fig.3, where 15.8 ps/div for the horizontal time axis, and 20 mV/div for the vertical eye height axis. Figure 4 shows the BER of FSK label with MSSI. Below 10^{-10} BER is achieved under the same received power in comparison with the case of the IM packet. The eye diagram of the FSK label with MSSI is also shown as an inset. A small waveform distortion is seen, which is due to the asymmetry of each tone of FSK about the respective peak, as can be seen in Fig.2. For the FSK label, the dispersion of fiber does not bring about much impact because only one tone of FSK with very narrow optical spectrum is filtered to detect. The low speed of the FSK label also strengthens the dispersion endurance. So, the BER and eye diagram of the FSK label without MSSI are omitted.

Conversion efficiency (CE) as a typical parameter for MSSI is also measured and depicted in Fig.5 versus wavelength detuning between the pump and the original

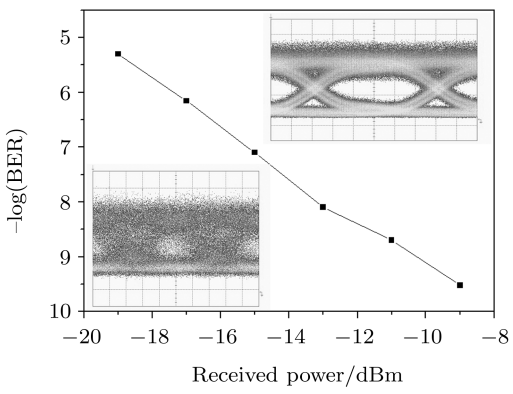


Fig.3. BER of IM packet versus received optical power with MSSI.

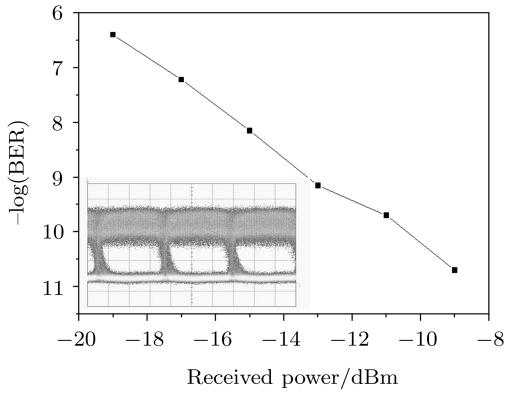


Fig.4. BER of FSK label versus received optical power with MSSI.

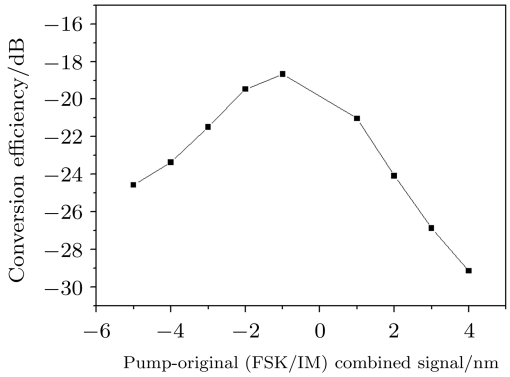


Fig.5. Conversion efficiency of combined FSK/IM signal versus wavelength detuning between the pump and the original FSK/IM signal.

FSK/IM combined signal with a constant optical power of −5.86 dBm and the previously mentioned fixed wavelength. It can be seen that about −19 dB of the highest CE is achieved for −1 nm down conversion. Here, one point that should be stressed is that a flat CE over a broad wavelength range can be achieved by some novel approaches,[8] which makes MSSI more practical in OLS networks based on multi-wavelength.

4. Conclusions

OLS based on FSK/IM combined modulation is a promising technique which is capable of saving the wavelength resource through putting the label and packet on a single optical wavelength. At the same time, the high speed packets are always processed in the optical domain so that the bottleneck effect of electronic processing can be avoided smoothly. However, the transmission length of high speed IM packets is severely limited by the fiber dispersion due to the broad optical spectrum of FSK label. The MSSI by four-wave mixing in a commercially available SOA with a length of about 1.5 mm is introduced to overcome the dispersion limitations. The experiment is carried out, where 155 Mb/s–10 Gb/s combined FSK-IM/Optical label-packet modulation signal is transmitted over 100 km standard single mode fiber using the proposed approach. In the experiment, below 10^{-10} and 10^{-9} BER are achieved for the FSK label and IM packet, respectively. −19 dB CE is obtained for −1 nm wavelength detuning.

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