Stealth Transmission of Time-Domain Spectral Phase Encoded OCDMA Signal Over WDM Network

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***Abstract*—Security enhancement of stealth channel by combining time-domain spectral phase en/decoding (SPE/D) OCDMA scheme and group velocity dispersion is proposed and experimentally demonstrated. The time-domain spectral phase encoded OCDMA signal, which utilizes a linearly chirped fiber Bragg grating for pulse broadening and a high-speed phase modulator for SPE, has been stealth transmitted over a public wavelength-division-multiplexing network. Error-free transmission (bit-error rate $< 10^{-9}$) has been achieved for both the public and stealth channel with 32-chip 40-Gchip/s gold codes.**

***Index Terms*—Optical code-division multiple-access (OCDMA), optical steganography, spectral phase en/decoding (SPE/D).**

I. Introduction

OPTICAL code-division multiple-access (OCDMA) technique has drawn considerable research interest over the past decades due to its unique advantages of high speed all-optical processing, fully asynchronous transmission with low-latency access, soft capacity on demand and so on [1], [2]. Providing information security is also considered an inherent advantage of OCDMA because the data are encoded into noise-like signals by using pseudorandom optical codes (OCs) assigned for each user during transmission [3], [4]. If the OC in the decoder is unmatched with that in the encoder, only a cross-correlation signal with low-level peak amplitude would be produced and the original data cannot be fully recovered.

Recently, we proposed a novel reconfigurable time-domain spectral phase encoding (SPE) scheme by using a pair of dispersive fibers with opposite dispersion and a high-speed phase modulator for coherent OCDMA application, and experimentally demonstrated 1.25-Gb/s on–off keying (OOK) data transmission with 16-chip 20-Gchip/s OCs [5]. An arrayed-waveguide grating (AWG)-based device was used as the spectral phase decoder. This technique is very robust to the wavelength drift of the laser source. Moreover, this scheme is very flexible in rapidly reconfiguring the OCs and is compatible with the fiber-optical system, exhibiting the potential to enhance the network security. To alleviate the control accuracy of the amplitude and phase of the AWG device, we further proposed a spectral phase encoding/decoding (SPE/D) OCDMA scheme for secure optical communication [6]. By using a linearly chirped fiber Bragg grating (LCFBG) to serve as the dispersive device, the SPE/D-OCDMA scheme is more compact and stable [7].

On the other hand, optical steganography is proposed to provide an additional layer of network security by hiding the existence of data transmission underneath a public channel, making it imperceptible in the public channel [8]. This strategy requires an all-optical public channel since any O-E conversion in the network would defeat the stealth signal transmission. Previously, a large amount of group velocity dispersion (GVD) was used to spread the stealth signal over time, and therefore, the peak power of the stealth signal becomes sufficiently below the level of the system noise [9]. It is not easy for an eavesdropper to restore the stealth signal from the public channel without the knowledge of the spreading function.

In this letter, we propose and experimentally demonstrate the security enhancement of stealth channel by combining the time-domain SPE/D OCDMA technique and GVD-based approach. The stealth channel is achieved by temporally broadening the pulse via GVD using an LCFBG and phase modulation with 32-chip 40-Gchip/s gold codes using a high-speed phase modulator. The generated OCDMA signal in the stealth channel can be fully hidden into the public wavelength-division-multiplexing (WDM) channel and spectral-phase-encoded simultaneously, making our scheme more compact and secure to stealth transmit the OCDMA signal over an existing public WDM network.

II. Principle of Proposed Scheme

Fig. 1 shows the experimental setup of the proposed scheme. In the experiment, the public WDM signal is generated by a continuous-wave (CW) laser at 1550.24 nm followed by an intensity modulator (IM) driven by $2^7 - 1$ pseudorandom bit sequences (PRBS) OOK data operating at 10 Gb/s. In the stealth channel, a mode-locked laser diode with a center wavelength of 1550.28 nm is used to generate a series of nearly transform-limited ~4-ps Gaussian-like optical pulse trains with a repetition rate of 10 GHz. An IM driven by $2^7 - 1$ PRBS is used to down convert the optical pulse repetition rate and generate the 1.25-Gb/s OOK data. The modulated pulse trains are then temporally broadened in the whole bit period of 800 ps through GVD by using an LCFBG with dispersion of −210 ps/nm and 3-dB bandwidth (BW) of ~4 nm for stealth channel hiding and optical encoding. Fig. 2(a) and (b) shows the spectrum and waveform of the broadened pulse with an average power of ~ −6 dBm after the LCFBG. Different spectral components spread into different positions in the time domain, thus the broadened waveform has the same temporal

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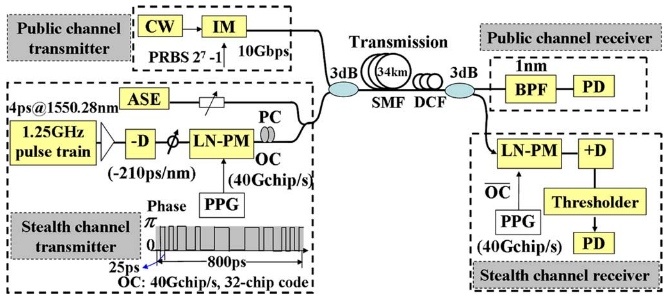

Fig. 1. Experimental setup of the stealth OCDMA signal transmission over public WDM channel.

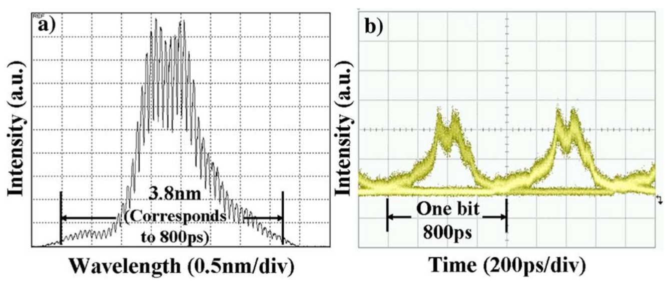

Fig. 2. (a) Spectrum and (b) waveform of the broadened pulse after the LCFBG.

profile as its spectrum. As shown in Fig. 2(a), the main 3.8-nm spectral range corresponds to one bit duration of 800 ps while the tail spectrum has very little effect on the pulse broadening. No obvious overlap between two adjacent broadened pulses has been observed, as shown in Fig. 2(b), due to the unique spectral response of the LCFBG which act as a dispersive device and bandpass filter (BPF) simultaneously. The spectral components out of the LCFBG's reflective spectrum have been cut off to avoid significant overlap between adjacent broadened pulses to improve en/decoding performance. The broadened pulse is then directed into a phase modulator driven by 32-chip 40-Gchip/s OC patterns (corresponding to 32-chip 15-GHz/chip spectral code patterns) to generate the time-domain spectral phase encoded stealth OCDMA signal. An optical delay line is used to guarantee the OC patterns precisely modulate the phase of the desired spectral component of the broadened pulse. Four different Gold codes with 31 chips plus a zero are used in the experiment: OC1: 100011000011 11001111010101001110, OC2: 111010110011000110111101 11111000, OC3: 00100101001010110010110010010000, and OC4: 10111001000111100000111001000110, respectively. Amplified spontaneous emission (ASE) noise from a separate erbium-doped fiber amplifier (EDFA) has been launched into the system to emulate the system noise in a real all-optical network. Then, the generated stealth signal is combined with the WDM signal by a 3-dB coupler and directed into a span of 34-km single-mode fiber (SMF) and dispersion-compensation fiber (DCF) for transmission.

At the receiver side, a 3-dB optical coupler is used to split the public and stealth signal into two portions. For the public channel detection, an optical BPF with 3-dB BW of 1 nm followed by a conventional energy detector is used, while for the stealth channel detection, the received signal is launched into the second phase modulator driven by the complementary code $\overline{\mathrm{OC}}$.

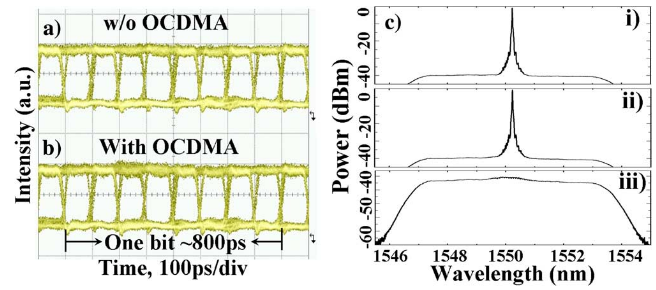

Fig. 3. Eye diagram of public WDM channel without (a) and with (b) stealth OCDMA signal; (c) spectrum of public WDM channel without (i) and with (ii) OCDMA signal and (iii) spectrum of stealth channel with ASE noise.

Synchronization between the encoding and decoding is highly required in order to correctly decode the stealth signal. Even if the stealth signal is revealed, it is still very difficult for an eavesdropper to correctly recover the stealth OCDMA signal without knowledge of the code used in the stealth channel and accurate time coordination. After that, another LCFBG with opposite dispersion of +210 ps/nm is used to compress the correctly decoded signal, such that the stealth channel appears above the public channel. Finally, a supercontinuum (SC)-generation-based optical thresholder [10] composed of a preamplifier EDFA and dispersion-flattened fiber (DFF) followed by a 5-nm BPF is used to extract the stealth OCDMA signal from the public WDM network.

III. Results and Discussion

A. Hiding and Restoring of OCDMA Signal

In the experiment, the stealth OCDMA signal can be temporally hidden underneath the WDM channel by properly adjusting the optical attenuator and polarization controller [8]. The average power ratio (Pr) of the public channel and stealth channel is about 13 dB. The eye diagrams of the public WDM channel without and with the stealth OCDMA signal are shown in Fig. 3(a) and (b), respectively. The resemblance of the two eye diagrams indicates that the stealth channel has been hidden in the public channel. The spectra of the public WDM channel without and with OCDMA signal are shown in Fig. 3(c) (i) and (ii), respectively. The two spectra are indistinguishable as well. The spectrum of the stealth channel is shown in Fig. 3(c) (iii). The peak power of the spectrum for the stealth channel is approximately 40 dB lower than that of the public channel.

In the stealth channel detection, the public WDM channel will also be phase-modulated and then temporally broadened by the LCFBG, and as a result, the public signal appears like a noise in the time domain. Fig. 4(a) shows the correctly decoded signal for OC2 with WDM signal. The stealth OCDMA signal has been recovered above the public WDM signal. The extracted OCDMA signal after the SC-based optical thresholder for the correctly decoded signal (a) is shown in Fig. 4(b). The public WDM signal has been significantly suppressed by the optical thresholding. Fig. 4(c) shows the waveform of the incorrectly decoded signal with public WDM signal. In contrast, the incorrectly decoded signal has a low signal-to-background ratio. The decoding performance is closely related to the 3-dB BW of the input spectrum before the LCFBG and residual dispersion (RD) during transmission. Fig. 4(d) shows the simulated

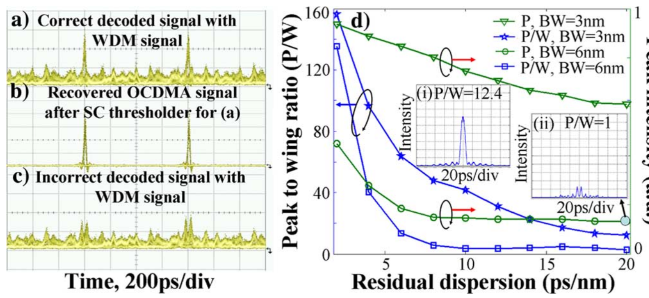

Fig. 4. (a) Correct decoded signal with WDM channel; (b) recovered stealth signal after thresholder; (c) incorrect decoded signal with WDM channel; and (d) peak-to-wing ratio (left) and peak intensity (right) of decoded waveform versus RD for different BW. Insets (i) and (ii) are the decoded waveforms for BW = 3 nm and BW = 6 nm with RD = 20 ps/nm.

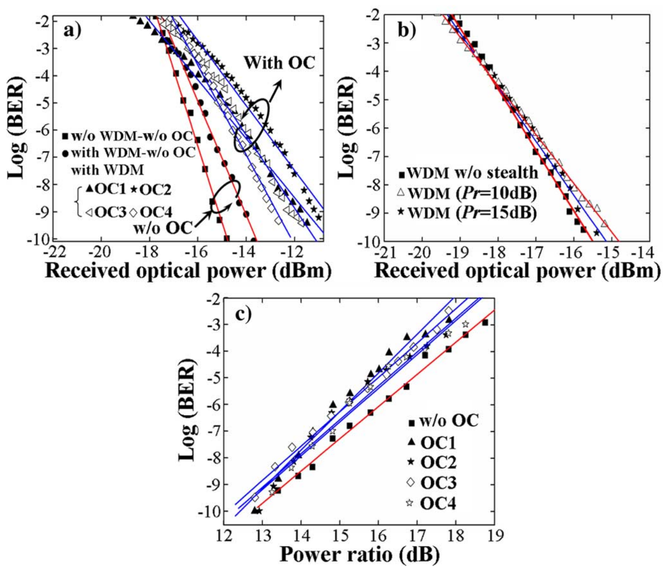

Fig. 5. (a) BER for stealth OCDMA channel with and without OC; (b) BER for public WDM channel; and (c) BER versus power ratio for stealth channel.

result of the RD and BW versus the peak-to-wing ratio (P/W) and peak intensity (P) of the decoded waveform for OC2. As the RD increases, the overlap (BW = 6 nm) will significantly degrade the decoding performance with lower P/W and P compared to that without overlap (BW = 3 nm). The insets (i) and (ii) show the decoded waveform for BW = 3 nm and 6 nm with RD = 20 ps/nm, from which one can see the encoded SPE signal can no longer be decoded for BW = 6 nm, while for the BW = 3 nm, P/W and P can still reach up to 12.4 and 0.6 for RD = 20 ps/nm, respectively. Higher RD can be tolerated in the absence of overlap. In our experiment, the LCFBG functions as a dispersive device as well as a BPF to cut the input spectrum into ∼4 nm to reduce the overlap and enable the decoding for an RD of ∼20 ps/nm that exists in the system.

B. BER Performance

The measured bit-error-rate (BER) of the stealth OCDMA signal is shown in Fig. 5(a). Error-free transmission has been achieved for the stealth channel with four different codes. In the absence of optical en/decoding, there is only ∼1-dB power penalty when the WDM signal is introduced. The optical en/decoding induces ∼2-dB power penalty due to the nonideal decoding. The discrepancy of BER performance for different OCs can be ascribed to the difference of decoding performance that will be affected by the RD, the overlap, and so on. The measured BER for the public WDM channel with different power ratio (Pr) is shown in Fig. 5(b). The effect of the OCDMA signal on the public channel is very small, and less than 1-dB power penalty is obtained when varying Pr between 10 and 15 dB. To investigate the influence of the public channel on the stealth channel, the BER performance of stealth channel for different Pr is also measured, as shown in Fig. 5(c). As Pr increases from 13 to 19 dB, the BER of stealth channel gradually degrades from 10^{-10} to 10^{-2}. By further compensating the RD and utilizing an identical phase modulator in both the encoding and decoding side to improve the decoding performance, a higher power ratio can be supported.

IV. Conclusion

We have proposed and experimentally demonstrated 1.25-Gb/s stealth OCDMA signal transmission over a 10-Gb/s public WDM channel. The stealth OCDMA channel is spectrally phase encoded in time domain using an LCFBG and phase modulator. The stealth channel is fully hidden in the public channel in both spectral and time domains. Error-free transmission has been achieved for both the stealth OCDMA channel and the public WDM channel. The proposed technique provides an effective and attractive approach for secure optical communication over an existing public WDM network.

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