Experimental demonstration of tolerance to FWM crosstalk in wavelength-swept WDM access systems

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Abstract: We confirm the tolerance of our proposed wavelength-swept wavelength division multiplexing (WDM) access system to four-wave mixing (FWM) crosstalk induced during fiber transmission. Since wavelength-swept light is employed as the carrier in the proposed system, there is little mutual interaction between different channel signals. Therefore, the tolerance to FWM crosstalk of the proposed technique is superior to that of conventional methods based on continuous-wave carriers. As a proof-of-concept, we perform experimental 10- and 20-km single-mode fiber transmissions of four-channel 1.25 Gb/s/ch WDM signals with a 12.5 GHz spacing, and show that FWM crosstalk has no serious impact even with a high optical power of +19 dBm.

Keywords: access network, dense wavelength division multiplexing (DWDM), wavelength sweep, four-wave mixing (FWM)

Classification: Fiber-optic communication

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1   Introduction

Wavelength division multiplexing (WDM) is a promising technique, especially as regards downlinks, that meets the growing demand for increased bandwidth and various types of services in the optical access network. In WDM-based access systems, granularity is an essential factor for the provision of high-capacity services and the flexible allocation of wavelength channels to users/services. Therefore, a cost-effective solution for super dense WDM [1, 2] will be needed in future access networks. In such a super dense WDM system, it is essential to employ a multi-wavelength optical transmitter that generates a number of wavelength channels, and precisely stabilizes their wavelengths. As a promising solution, we have already proposed a multi-wavelength optical transmitter with a simple configuration based on the use of wavelength-swept light [3]. With the proposed method, super dense WDM signals can be realized by the time-domain modulation of wavelength-swept light using a single light source and modulator without the need for WDM filters.

In this Letter, we confirm the tolerance of the proposed wavelength-swept WDM access system to non-linear inter-channel crosstalk induced by four-wave mixing (FWM) during transmission [4]. With the proposed approach, since wavelength-swept light is employed as the carrier, plural channel signals do not exist simultaneously; namely there is little mutual interaction between different channels. Therefore, the tolerance of the proposed technique to FWM crosstalk is expected to be superior to that of conventional WDM systems based on continuous-wave (CW) carriers. As a proof-of-concept, we demonstrate the 10- and 20-km single-mode fiber (SMF) transmission of four-channel 1.25 Gb/s/ch WDM signals with a 12.5 GHz spacing, and show that the FWM crosstalk has no serious impact even with a very high launch power.

2   Tolerance to FWM crosstalk in wavelength-swept WDM

With the proposed WDM transmitter, we used a wavelength-swept light source and a modulator, as shown in Fig. 1 (a), and we obtained a WDM signal by modulating the wavelength-swept light with a signal that we generated by time-domain multiplexing the data of each channel [3]. With this method, we can realize a super dense WDM signal with a spacing of 12.5 GHz using a simple configuration and without the need for WDM filters.

In such dense WDM systems there is a problem of inter-channel crosstalk induced by fiber non-linearity and this limits the signal quality. Of the factors
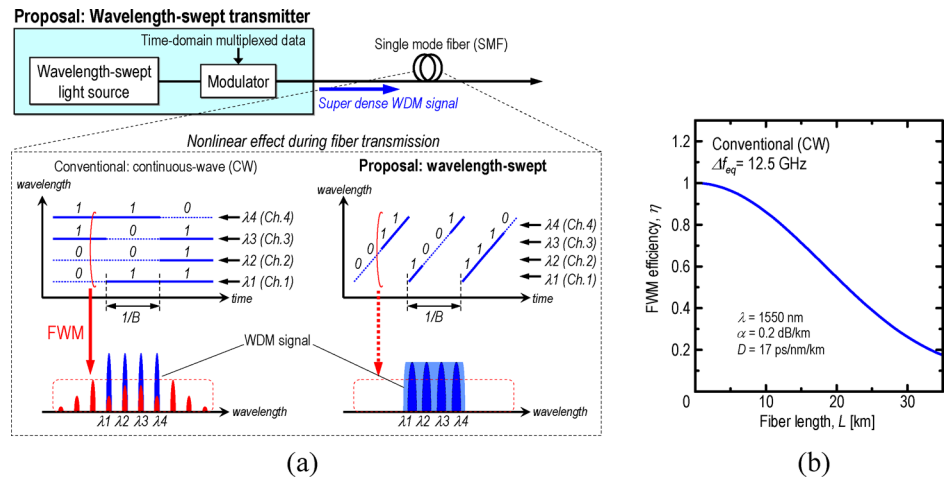
Fig. 1. (a) Schematic of FWM crosstalk in wavelength-swept WDM system, (b) Calculated relation between fiber length, L, and FWM efficiency, η, for conventional WDM systems with Δf_{eq} of 12.5 GHz.

that induce crosstalk, FWM is expected to be the most detrimental to super dense WDM access systems, where the bit rate of each channel ($\sim$Gb/s) and the fiber length ($\sim$20 km) are moderate and the channel spacing is very small ($\sim$0.1 nm). The FWM depends on the phase matching condition between the plural wavelength channels, therefore its efficiency is determined by the channel spacing and fiber dispersion, as shown in Eq. (6) in [4]. Fig. 1 (b) shows the calculated relationship between the efficiency of the FWM of three waves (frequency f_i, f_j, and f_k), η, and fiber length, L, for conventional WDM based on CW carriers. Here, the equivalent frequency separation [4], $\Delta f_{eq}(ijk)$, is 12.5 GHz, and the wavelength, fiber attenuation, and dispersion, are set at $\lambda = 1550$ nm, $\alpha = 0.2$ dB/km, and $D = 17$ ps/nm/km, respectively. This result shows that, even if we use the 1.5-μm band in the access networks and 1.3-μm zero-dispersion SMF with a maximum length of 20 km, we cannot ignore the impact of FWM crosstalk in super dense WDM systems.

On the other hand, when we consider the time-wavelength relation with the proposed technique, since wavelength-swept light is used as the carrier, plural channel signals do not exist simultaneously, whereas, in conventional WDM systems, all channel signals co-exist at any given time, as shown in Fig. 1 (a). This means that, unlike with the conventional WDM systems mentioned above, there will be hardly any mutual interaction between different channels during transmission, and the impact of FWM can be largely eliminated. As a result, we can expect the proposed technique to have superior tolerance to that of conventional WDM systems, and be capable of transmitting high power WDM signals without serious signal degradation.

3   Experiments and results

To compare the impact of FWM crosstalk with the two approaches, we undertook a four-channel 1.25 Gb/s/ch WDM transmission experiment with a
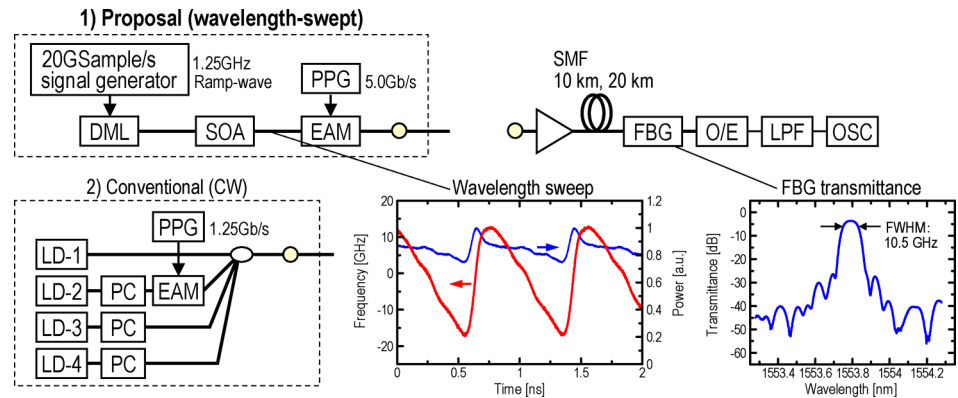
Fig. 2. Experimental setup for four-channel 1.25-Gb/s WDM transmission; DML: direct modulated laser, SOA: semiconductor optical amplifier, PPG: pulse pattern generator, EAM: electro absorption modulator, LD: laser diode, PC: polarization controller, FBG: fiber Bragg grating filter, O/E: optical/electrical convertor, LPF: low-pass filter, OSC: oscilloscope.

spacing of 12.5 GHz using both 1) the proposed technique and 2) the conventional method as shown in Fig. 2. With the proposed method, a distributed feedback laser diode was directly frequency-modulated by a 1.25 GHz ramp-wave signal.

A semiconductor optical amplifier (SOA) after a laser operated under a gain-saturated condition to suppress the intensity modulation effect. As a result, we obtained a 1.25 GHz wavelength-swept light with a wavelength sweep range of approximately 30 GHz, as shown in the Fig. 2 inset. The wavelength-swept light was modulated with a 5.0 Gb/s (1.25 Gb/s/ch × 4 channels) pulse pattern signal at an electroabsorption modulator (EAM). The pulse pattern has a 32-bit fixed sequential pattern so that only ch.2, which is an inner channel with adjacent signals on either side (shorter and longer wavelengths), was modulated with an 8-bit fixed pattern [10101100], and other channels were constantly modulated with a mark bit [1]. The total power of the modulated optical signal (four-channel WDM) was set at +13.0 dBm by using an erbium-doped fiber amplifier. In contrast, four lasers were used with the conventional method and their wavelength channel spacing was set at 12.5 GHz. Polarization controllers (PC) were used to set the polarization states of the four optical signals so that they were identical. And, as with the proposed method, only the optical signal of ch.2 was modulated with a 1.25 Gb/s pulse pattern (8-bit: 10101100). The power of each channel was set at +5.0 dBm (approximately +11.0 dBm in total). The four-channel WDM signal was transmitted through a 10-km long SMF after amplification, and then the optical signal of ch.2 was extracted by a fiber Bragg grating (FBG) filter with a full width at half maximum bandwidth of 10.5 GHz as shown in Fig. 2.

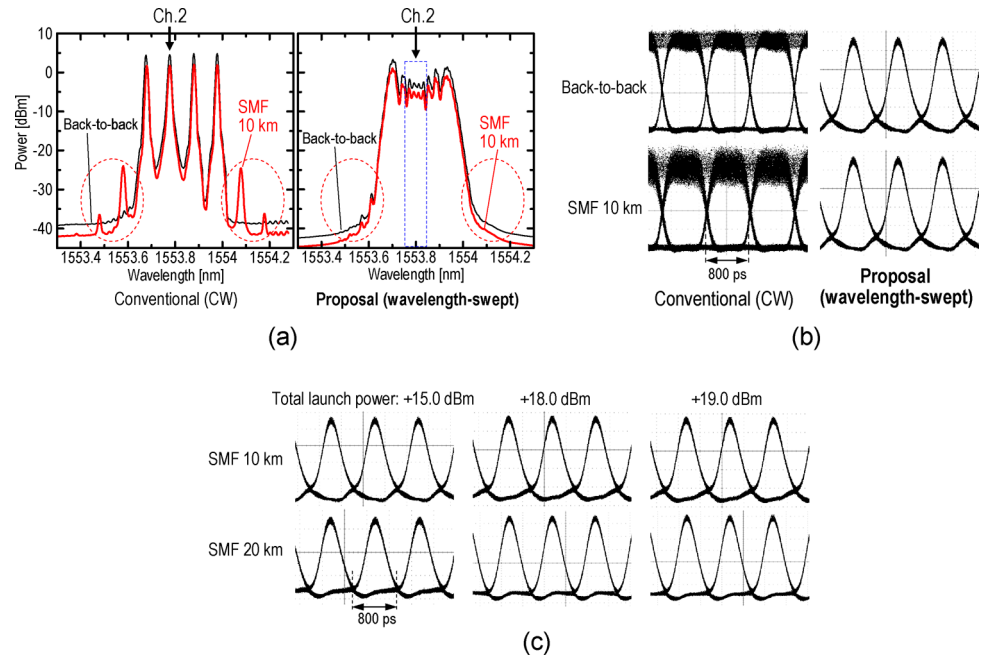Optical spectra of the WDM signal for both back-to-back and 10-km SMF

Fig. 3. (a) Optical spectra for back-to-back and 10-km SMF transmissions, (b) 1.25-Gb/s eye diagrams of ch.2 with conventional and proposed techniques, (c) eye diagrams of ch.2 with proposed technique with high launch power after 10-km and 20-km SMFs.

transmissions are shown in Fig. 3 (a). With the conventional method, we can see the newly generated signals that were induced by FWM during the 10-km SMF transmission. And, we can expect that such FWM-induced signals also appeared in the WDM signal bandwidth (1553.6 to 1554.0 nm). On the other hand, there were no FWM-induced signals with the proposed method, even though the total power was as high as +13.0 dBm at the SMF input. As mentioned in section 2, this result indicates that there was almost no FWM during fiber transmission.

Fig. 3 (b) shows 1.25-Gb/s eye diagrams of ch.2 for both methods. We can see that, there was no noticeable degradation in the eye opening after fiber transmission with the proposed method, whereas with the conventional method, the eye opening deteriorated owing to the FWM crosstalk. Furthermore, we examined the tolerance to FWM of the proposed method for a higher launch power. For example, if we can launch higher power in the passive optical network (PON) systems, we can accommodate larger number of users by using power splitters with high splitting number. With the same experimental setup, we set the total launch power at +15.0 to +19.0 dBm, and used two SMFs with lengths of 10 and 20 km. In each case, by measuring the transmitted optical power at the fiber output, we confirmed that there was no deterioration in the transmitted power resulting from stimulated Brillouin scattering (SBS). Eye diagrams of ch.2 measured after SMF transmission are shown in Fig. 3 (c). We can see that, even though the launch power was increased to +19.0 dBm in total, which is near the eye safety limit in the 1.5-μm

band (+21.3 dBm) [5], there were no noticeable changes in the eye openings for either fiber length. Here, when we consider the dependence of the number of channels (N), the number of FWM-induced components increases with the cube of N [6]. On the other hand, since the FWM is the third-order non-linear phenomenon, the resulting power of each FWM-induced component is proportional to the cube of launch power of each channel signal. This means that, when the total launch power identical, since the power of each channel signal decreases to 1/N, there is no significant dependence on the number of channels. And, since the maximum fiber length in the access networks is 20 km, we expect that these experimental results are sufficient as proof-of-concept demonstrations for the access networks. These results confirm that the tolerance of the proposed technique to FWM crosstalk is superior to that of the conventional WDM method.

4   Conclusion

We examined the tolerance of our proposed wavelength-swept WDM system to non-linear inter-channel crosstalk induced by the FWM process during fiber transmission. With the proposed technique, since wavelength-swept light is employed as a carrier, plural channel signals do not exist simultaneously. Therefore, the tolerance to FWM crosstalk of the proposed technique is expected to be superior to that of conventional WDM systems based on CW carriers. As a proof-of-concept, we experimentally demonstrated the 10- and 20-km SMF transmission of a four-channel 1.25-Gb/s/ch WDM signal with a 12.5-GHz spacing, and the results showed that the FWM crosstalk had no serious impact even when the transmitting power was around +19 dBm.