12.5-GHz Spaced 1.28-Tb/s (512-Channel × 2.5 Gb/s) Super-Dense WDM Transmission Over 320-km SMF Using Multiwavelength Generation Technique

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***Abstract*—We achieve a 512-channel super-dense wavelength-division-multiplexing (WDM) transmission with a 12.5-GHz channel spacing over 320 km (80 km × 4) of standard single-mode fiber in the $C + L$-bands. Optical carrier supply modules, which are based on a flattened sideband generation scheme, are applied to generate the 512 wavelengths from only 64 distributed-feedback laser diodes with a frequency spacing of 100 GHz. Arrayed-waveguide gratings with a 12.5-GHz spacing are used in this super-dense WDM experiment.**

***Index Terms*—Arrayed-waveguide grating, multiwavelength generation, optical fiber communication, wavelength-division-multiplexing.**

I. Introduction

With the increasing demand for wavelength-division-multiplexing (WDM) transmission capacity, many WDM experiments with a total capacity of over 1 Tb/s have been recently reported at the bit rate of 10 Gb/s [1] and 40 Gb/s [2], [3]. There are two approaches to increase the total capacity per optical amplifier bandwidth. One is increasing the bit rate per channel, and the other is increasing the number of channels by incorporating a narrower channel spacing. The latter approach is based on a relatively lower bit rate per channel, as compared to the former, thus leading to the following advantages: 1) no complicated dispersion compensation technique is required; 2) relatively low-speed electrical circuits can be used; and 3) the nonlinear effect of fibers may be mitigated because the required fiber input power is reduced. Several technical issues, however, have emerged in realizing high-capacity super-dense WDM transmission with narrower channel spacing and are listed as follows: 1) how to install a large number of optical sources; 2) development of multi/demultiplexers with a narrow passband; and 3) compact implementation of a large number of modulators and receivers.

This letter addresses technical issues 1) and 2) above. We describe compact optical carrier supply modules (OCSMs) based on a novel multiwavelength generation technique, which is used to generate 512 flattened sidebands with a frequency spacing of 12.5 GHz from only 64 distributed-feedback laser diodes (DFB-LDs). Arrayed-waveguide gratings (AWGs) with a channel spacing of 12.5 GHz were developed. By using the OCSMs and AWGs, a 12.5-GHz spaced 512-channel super-dense WDM transmission experiment was successfully carried out over 320 km (80 km × 4) of single-mode fiber (SMF) without dispersion compensation in the $C + L$-bands.

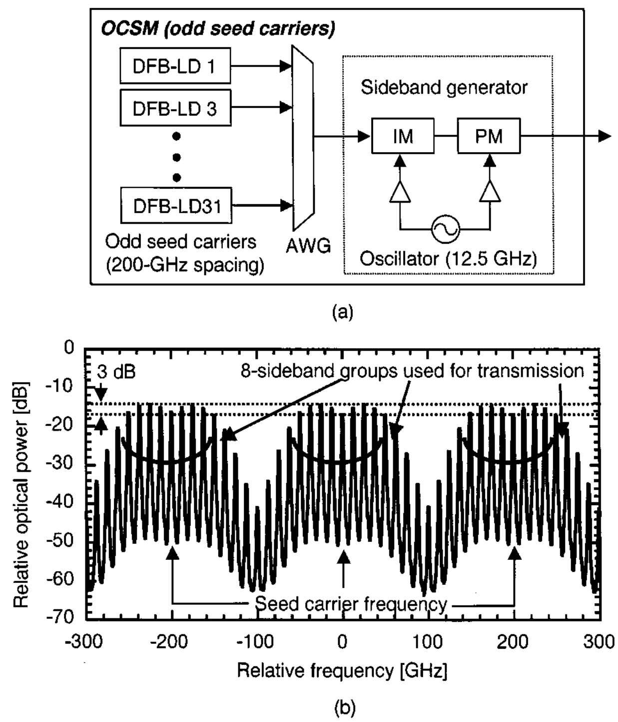

Fig. 1. (a) Basic configuration of OCSM. (b) Output spectra from the OCSM with a frequency spacing of 12.5 GHz.

II. Optical Carrier Supply Module (OCSM)

Fig. 1(a) shows the basic configuration of an OCSM used to generate the 12.5-GHz spaced flattened sidebands [4]. DFB-LDs, which are utilized as seed carriers, are frequency controlled using ITU-T grid frequencies at a spacing of 100 GHz. Odd seed carriers with a frequency spacing of

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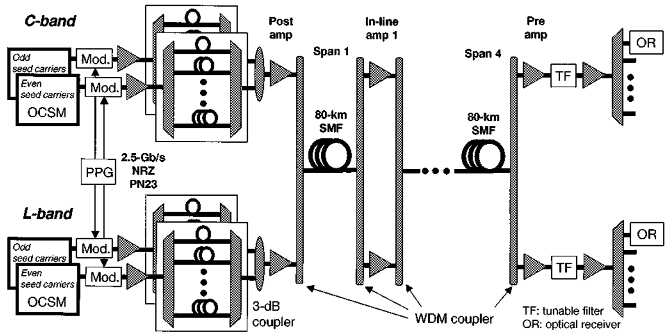

Fig. 2. Experimental configuration for 12.5-GHz spaced 512-channel super-dense WDM transmission employing OCSMs.

200 GHz are multiplexed by an AWG and input into a sideband generator comprising an intensity modulator (IM), a phase modulator (PM), a 12.5-GHz oscillator, and electrical amplifiers. Fig. 1(b) is an example of the spectra output from the sideband generator. As shown in Fig. 1(b), the deviation in the optical power level is suppressed to less than 3 dB in nine sidebands generated by a seed carrier. The eight sideband groups generated from the seed carriers, as shown in Fig. 1(b), were used for transmission, and the remaining sidebands were filtered out to eliminate the crosstalk.

III. Experimental Configuration

Fig. 2 shows the experimental configuration for the 12.5-GHz spaced 512-channel super-dense WDM transmission employing OCSMs. Two wavelength bands (C-band and L-band) were used and 256 channels were produced from 32 seed carriers by utilizing two OCSMs in each wavelength band. The 32 seed carriers with a frequency spacing of 100 GHz ranged from 1535.82 nm (195 200 GHz) to 1560.61 nm (192 100 GHz) in the C-band and 1572.89 nm (190 600 GHz) to 1598.89 nm (187 500 GHz) in the L-band. The flattened sidebands generated by the OCSMs were modulated at 2.5 Gb/s using a $2^{23} - 1$ nonreturn-to-zero (NRZ) pseudorandom bit sequence. The modulated signals were demultiplexed by an AWG and the bit patterns were decorrelated so that about ten bits were delayed for each adjacent channel. The 128 decorrelated channels were multiplexed again by an AWG and input into a 3-dB coupler. The channel spacing and the 3-dB bandwidth of these AWGs were 12.5 and 7.5 GHz, respectively [5]. The transmission line was 320 km (80 km $\times$ 4 span) of SMF and the span loss was 16 dB at the wavelength of 1550 nm. No dispersion compensation fiber was used. On the receiver side, an optical tunable filter (TF) and a 12.5-GHz spaced AWG were cascaded to achieve the required wavelength extraction. The adjacent channel crosstalk of the AWG was less than -20 dB. The optical signal-to-noise ratios (OSNRs) with a resolution of 0.02 nm were more than 26 dB in back-to-back transmissions.

IV. Numerical Analyses and Experimental Results

Before the experiment, the Q-factors against fiber input powers were numerically calculated in order to determine the optimum fiber input power. The number of channels and the bit rate were 256 and 2.5 Gb/s, respectively. The chromatic

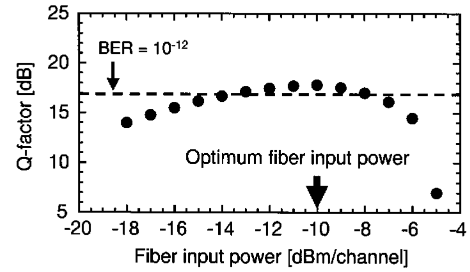

Fig. 3. Calculated Q-factor against fiber input power after 320-km transmission.

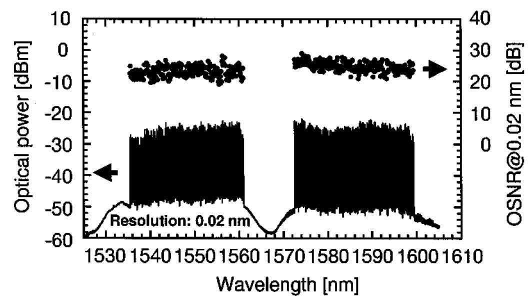

Fig. 4. Optical spectra and OSNRs versus wavelength after 320-km transmission.

dispersion was 16 ps/nm/km at the center signal wavelength and the nonlinear coefficient was 1.4/W/km. The noise figure of the optical amplifiers was 8 dB. The other simulation parameters were set to be almost the same as those in the experiment. Fig. 3 gives the calculated Q-factors against various fiber input powers after 320-km transmission. The Q-factor of the worst channel is plotted at each fiber input power. The Q-factor was greatest at the fiber input power of -10 dBm/channel. When the fiber input power was increased to more than -10 dBm/channel, the transmission performance degraded due to the nonlinear effect of fibers. When the fiber input power was in the region between -8 to -13 dBm/channel, it was found that the Q-factor was greater than 16.9 dB, which corresponds to a bit error rate of 10^{-12}.

Based on numerical analyzes, the 12.5-GHz spaced WDM transmission experiment was conducted at the average fiber input power of -10 dBm/channel. The OSNRs for all channels and the optical spectra were measured after the 320-km transmission as shown in Fig. 4. The OSNRs of all the channels with a resolution of 0.02 nm were between 19.1 and 28.2 dB in the C-band and between 20.9 and 29.0 dB in the L-band. Typical eye diagrams in both wavelength bands are given in Fig. 5 [Fig. 5(a) Channel-128 in the C-band and Fig. 5(b) Channel-392 in the L-band]. Clear eye openings were observed using 12.5-GHz spaced AWGs.

To evaluate the transmission performance, the Q-factors were measured for more than 120 channels and error free transmission was confirmed. First, we measured the Q-factors for the 64 channels, each of which had the worst OSNR among the eight sidebands generated by a seed carrier. The measured Q-factors against the wavelengths are represented by closed circles in Fig. 6(a). The obtained Q-factors were greater than 17.0 dB, which corresponds to a bit error rate (BER) of below 10^{-12}, and

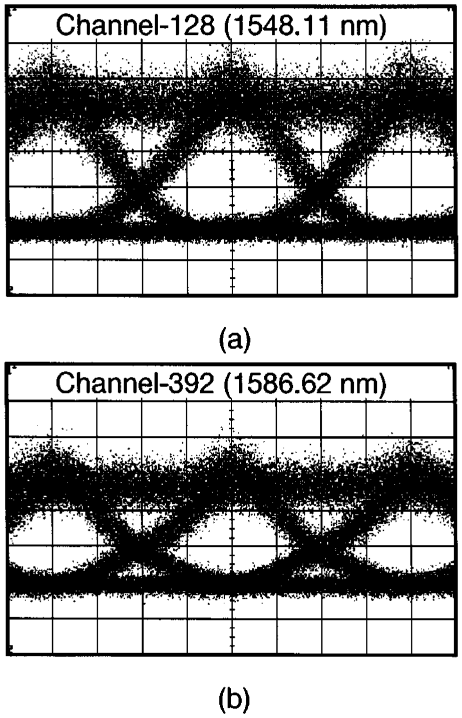

Fig. 5. (a) Eye diagram of Channel-128 in the C-band and (b) that of Channel-392 in the L-band.

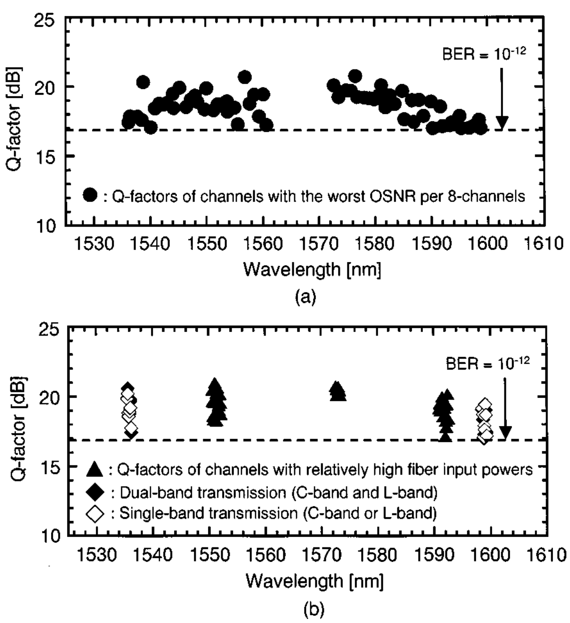

Fig. 6. Q-factors versus wavelength after 320-km transmission from viewpoint of (a) OSNR and (b) nonlinear effect of fibers.

agreed well with the simulation results. Next, we evaluated the performance degradation due to the nonlinear effect of transmission fibers, four-wave mixing (FWM), self-phase modulation (SPM), and cross-phase modulation (XPM). From the results of the transmitted spectra shown in Fig. 4, the Q-factors for 40 channels with relatively high fiber input powers were measured (eight consecutive channels in the shortest wavelength region in the L-band and 16 consecutive channels in the vicinity of the center signal wavelength region of the individual wavelength bands). These results are represented by closed triangles in Fig. 6(b). The Q-factors were greater than that for the channel with the worst OSNR in the same seed carrier and it was found that no significant degradation was exhibited due to the nonlinear effect of fibers in this experiment. Finally, we confirmed the effect of stimulated Raman scattering (SRS) between the C-band and L-band. The Q-factors for the eight consecutive channels with the shortest wavelength region in the C-band and those for the eight consecutive channels with the longest wavelength region in the L-band were measured. Closed and open diamonds represent the Q-factors when signals in the two wavelength bands were transmitted simultaneously and separately, respectively, as shown in Fig. 6(b). The penalty was less than 0.5 dB at most and there is no significant degradation due to the SRS effect. This is because the low average fiber input power of -10 dBm/channel was adopted in both wavelength bands, particularly in the L-band.

V. Conclusion

By applying 12.5-GHz spaced AWGs and the OCSMs based on a multiwavelength generation technique, we successfully demonstrated a 12.5-GHz spaced 1.28-Tb/s (512-channel × 2.5 Gb/s) super-dense WDM transmission over 320 km of SMF in the $C + L$-bands. Error free operation with a BER of 10^{-12} was achieved without dispersion compensation. No significant degradation due to the nonlinear effect of fibers (FWM, SPM, XPM and SRS) was observed in this experiment because the average fiber input power was reduced to -10 dBm/channel.

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