

Wideband WDM Erbium-doped Optical Fiber Amplifiers for 10 Gb/s, 32-channel SMF Transmission Systems

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We have developed novel wide-dynamic-range WDM optical fiber amplifiers for 10 Gb/s, 32-channel SMF transmission systems. These amplifiers consist of a low-noise pre-amplifier section, a mid-attenuator for loss compensation of a dispersion compensator and ALC operation, and a post-amplifier section for a high output power. These WDM amplifiers are also designed to allow in-service channel upgrades and in-service accommodation of external pump units. We have confirmed the superior performance of these WDM amplifiers by performing 320 Gb/s (10 Gb/s ×32-channel) transmissions over 320 km (80 km ×4 span) of SMF, achieving a bit error rate of less than 10^{-15} for all channels.

1. Introduction

Wavelength-division-multiplexing (WDM) systems have become one of the major solutions to meet the growing demand for increased network bandwidth brought about by the rapid growth of Internet and data services. Wideband optical fiber amplifiers are essential for WDM trunk-line systems because of their broad gain bandwidth, low noise, and good high-power characteristics.

We focus on developing WDM amplifiers that not only satisfy high-capacity requirements but also make it possible to fully realize the potential of WDM technology, for example, flexible, less-expensive, scalable services.^{1),2)} The developed amplifiers are intended for a 1.3 μm zero-dispersion single-mode fiber (SMF) transmission system. This is because most of the embedded fiber cable in use is SMF, especially in capacity-demanding North America. Moreover, because a WDM amplifier for SMF requires more functions than any other WDM amplifier, for example, the accommodation of a dispersion compensator, the

technologies employed for them are applicable to any other WDM amplifier. SMF has a large chromatic dispersion of about 18 ps/nm/km at 1.55 μm , so dispersion compensation is indispensable for high-speed channel rate (10 Gb/s) transmission. In addition, WDM optical fiber amplifiers must maintain a flat-gain and control the output power of each channel, referred to as "per carrier automatic level control (ALC) operation" to compensate for the span-loss variation encountered in practical systems. Because the signal power is controlled at the output of the amplifier, the span-loss variation therefore causes power variations at the amplifier input. The spectral-gain change caused by input level variations is called "dynamic gain-tilt." We outline these issues first and then explain our proposed WDM optical fiber amplifiers which answer the above issues. We also propose a novel channel upgrade method using the proposed WDM amplifiers and the standardized Optical Supervisory Channel (OSC) system.

2. Requirements for Wideband WDM Optical Fiber Amplifiers

In addition to the features required in a single-channel optical amplifier (e.g., low noise and good high-power characteristics), WDM optical fiber amplifiers must have the following:

- 1) Broad gain bandwidth for simultaneously amplifying many signals in 32 wavelengths
- 2) Gain flatness over a wide input power range
- 3) Output power controllability of each amplified signal
- 4) Loss compensation of dispersion compensators
- 5) Output power stability during an increase or decrease in the number of channels
- 6) A smooth upgrade scheme for an increase or decrease in the number of channels.

Among these requirements, the second and third are especially important when WDM amplifiers are used as optical repeaters. In optical-amplifier repeated systems, the output power of each channel at the amplifier should be kept within the optimum level window to avoid excessive generation of nonlinear effects and a deterioration of the signal-to-noise ratio (SNR) as optical signals travel along the transmission fiber (**Figure 1**).

Taking account of their simple and cost-effective configuration, WDM optical amplifiers are likely to be used to control the total output power instead of the output power of individual channels. The wide dynamic input range of WDM amplifiers with the spectrally-flattened gain therefore becomes essential in the total output-

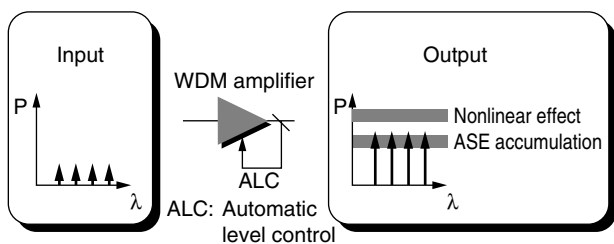


Figure 1 Window of optimum output level in optically amplified transmission.

power control scheme, which allows the same amplifier to be applied to various span-loss sections. **Figure 2** shows the spectral gain of an erbium-doped fiber (EDF) at various inversion rates. Owing to the homogeneously broadening characteristic of the EDF, the spectral shape is fixed if the average-gain or the inversion rate is clamped. Thus the combination of gain-clamped EDFs and passive optical gain equalizers (GEQs) provides a spectrally-flattened gain over a wide range of input power. However, in this combination, the total output power varies with the input power, which means that there is no ALC function. We therefore introduce a variable optical attenuator to overcome this problem. The aforementioned combination technology fixes the spectral characteristics and provides attenuation for the ALC operation. We realize per carrier ALC operation by total-power ALC operation based on the number of operation channels. Requirements 5) and 6) relate to the flexibility and scalability of the WDM system. The ability to perform channel upgrades without affecting the surviving channels is an indispensable requirement for reducing the initial investment and realizing a cost-effective WDM system.

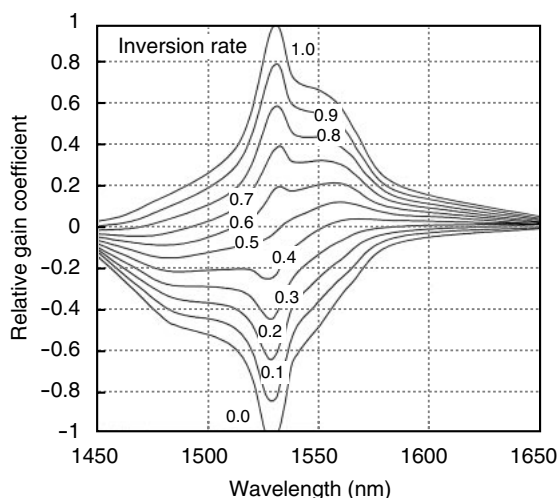


Figure 2 Spectral-gain at various inversion rates.

3. Key Elements for WDM Optical Fiber Amplifiers

3.1 Alumina highly co-doped erbium-doped fiber

EDF is designed to obtain a maximally flattened spectral-gain over the entire signal band. To flatten the spectral-gain, aluminum (Al) is highly co-doped with erbium (Er). The Al concentration is optimized because too much concentration produces a gain-dip around 1545 nm. Consequently, we achieve a flattened spectral-gain characteristic of over 30 nm from 1530 nm to 1565 nm in which the gain deviation between the maximum and minimum is reduced to 4 dB from 6.5 dB at a 30 dB average-gain operation. Furthermore, the efficiency is improved by reducing the background loss from 20 dB/km to 6 dB/km through optimization of the manufacturing conditions. The polarization mode dispersion (PMD), which is another important characteristic, is less than 0.05 ps per 10 m. This value is low enough for high-speed (10 Gb/s) optical network systems.

3.2 Non-mechanical variable optical attenuator

To increase the dynamic input range of the WDM amplifier, ALC operation based on a specially developed variable attenuator³⁾ plays an important role. The variable attenuator consists of two polarizers and a Faraday rotator as shown in Figure 3.

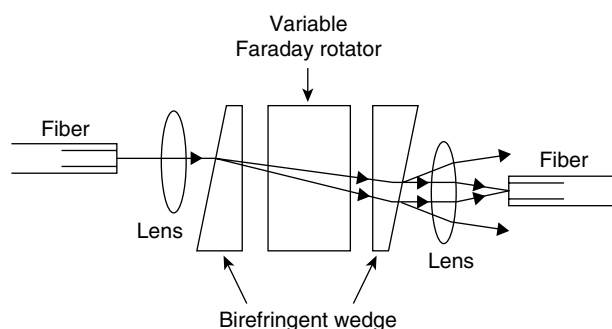


Figure 3
Non-mechanical variable optical attenuator using Faraday effect.

The rotation-angle of the polarization is controlled by varying the driving current of the rotator. Because the operating wavelength is 1.55 μm , the most efficient Faraday rotator is made of iron garnet crystal. However, it is impossible to control the magnitude of the magnetization continuously under magnetic saturation because iron garnet is ferromagnetic. On the other hand, if the magnetization is not saturated, the crystal causes scattering and has magnetic hysteresis. Our non-mechanical variable attenuator utilizes a novel method of controlling the Faraday rotation angle. If the angle between the direction of magnetization and light propagation is θ , the Faraday rotation is proportional to $\cos\theta$. A continuous change in the magnetization direction is thus possible even under magnetic saturation by the variable Faraday rotation. A significant feature of the proposed method is good continuousness with no scattering or hysteresis. The variable Faraday rotator is inserted between two birefringent wedges as shown in Figure 3, which is the same as the scheme used in an inline optical isolator to eliminate the polarization dependence. The first wedge refracts the input light collimated by a lens, with the ordinary and extraordinary light being deflected at different angles. After the Faraday rotation, a part of each light beam couples again to the output fiber by refraction in the second wedge. The amount of coupling to the output fiber is determined by the degree of Faraday rotation. Thus, current-driven variable attenuation is realized without polarization dependence.

A current of 0 to 50 mA drives the attenuator from the minimum attenuation (0.8 dB) to the maximum attenuation (25 dB). Without a fiber cover, the attenuator is 23 mm long, 25 mm wide, and 8 mm high.

4. Wide-dynamic-range WDM Optical Fiber Amplifiers

The proposed WDM optical fiber amplifiers have the following features:

- 1) A flat-gain bandwidth over 25 nm for 32

- wavelengths in an ITU-T 100 GHz grid
- 2) Per carrier grid-to-grid automatic level control (ALC) operation^{4,5)} over a 7 dB input power range
- 3) Field-installation of dispersion compensator by automatic loss compensation⁵⁾
- 4) Flexible configuration allowing the field-installation of external pump units
- 5) Scalability for the number of wavelengths by using an ALC/AGC switching scheme⁶⁾
- 6) Simple and cost-effective configuration

Figure 4 shows the configuration of the proposed WDM optical fiber amplifier. The amplifier consists of a low-noise pre-amplifier, a mid-attenuator for ALC operation, and a post-amplifier for a high output power. The AGC scheme is employed in both the pre- and post-amplifier sections in order to keep the spectral-gain constant over input power variations. Two gain equalizers, GEQ1 and 2, are used to flatten the gain over the entire signal band of 32 wavelengths (1535.8 to 1560.6 nm) for the pre-amplifier and post-amplifier, respectively. A dispersion compensator (DC) is employed between the pre-amplifier and the post-amplifier. Using the connector interface with the DC, the amplifier provides the flexible accommo-

modation of many kinds of DCs. The configuration of two separated and gain-flattened blocks with DC not only provides a high SNR in each channel but also makes it easy to fabricate and test the amplifiers. It also reduces the production list of the amplifiers by combining different pre- and post-amplifiers. The variable optical attenuator (VAT) using the Faraday effect absorbs the span-loss and DC loss variations to realize ALC operation. When the number of wavelengths is increased, the amplifier can accommodate external pump units in the post-amplifier during operation; this is one of the remarkably smooth upgrade functions of these amplifiers. The optical supervisory channel (OSC) section is attached to the amplifier section, which demultiplexes the supervisory channel (λ_{sv} :1510 nm) at the input and multiplexes it at the output. The OSC collects supervisory information of each unit and carries it downstream. Figure 5 shows a photograph of the amplifier section.

Several kinds of DCs have been proposed. Among them, a dispersion compensating fiber (DCF) is promising for its wideband compensation characteristic and stability against ambient temperature variation. There are two problems

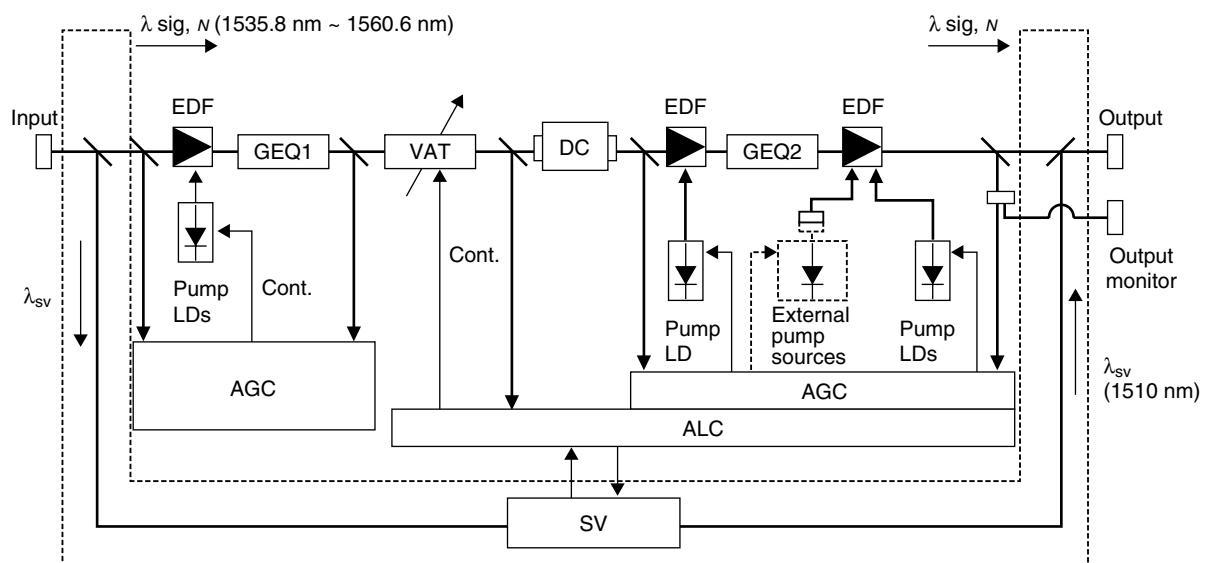


Figure 4
WDM optical fiber amplifier for 10 Gb/s ×32-channel SMF transmission.

in the application of the DCF. One problem is the relatively large optical loss (~10 dB) of the DCF and its loss dependence on the amount of compensating dispersion. The other problem is the generation of nonlinear effects in the DCF because of its small mode-field diameter and long length. This problem restricts the input power applied to the DCF to less than 0 to -2 dBm/ch.⁷⁾

The DCF loss is compensated for in the pre-amplifier and mid-attenuator section. The proposed amplifier also overcomes above problems. It realizes ALC operation by automatically compensating for the DCF loss as shown in **Figure 6 (a)**. First, the pre-amplifier sufficiently amplifies the WDM signals at low noise. The variable optical attenuator (VAT) reduces the input power to the DCF to below the allowed maximum. At the same time, it controls the input power of the post-amplifier. Although the detailed control lines are omitted in Figure 4, the input-level of the post-amplifier is adjusted to a pre-determined level (controlled level) in the initializing process.

After initialization, the VAT is controlled mainly by feedback derived from the input to the DCF in Figure 4. The control level is determined from the allowed maximum input power (for example, -3 dBm/ch) and from the maximum DCF loss in-



Figure 5 Photograph of proposed WDM amplifier.

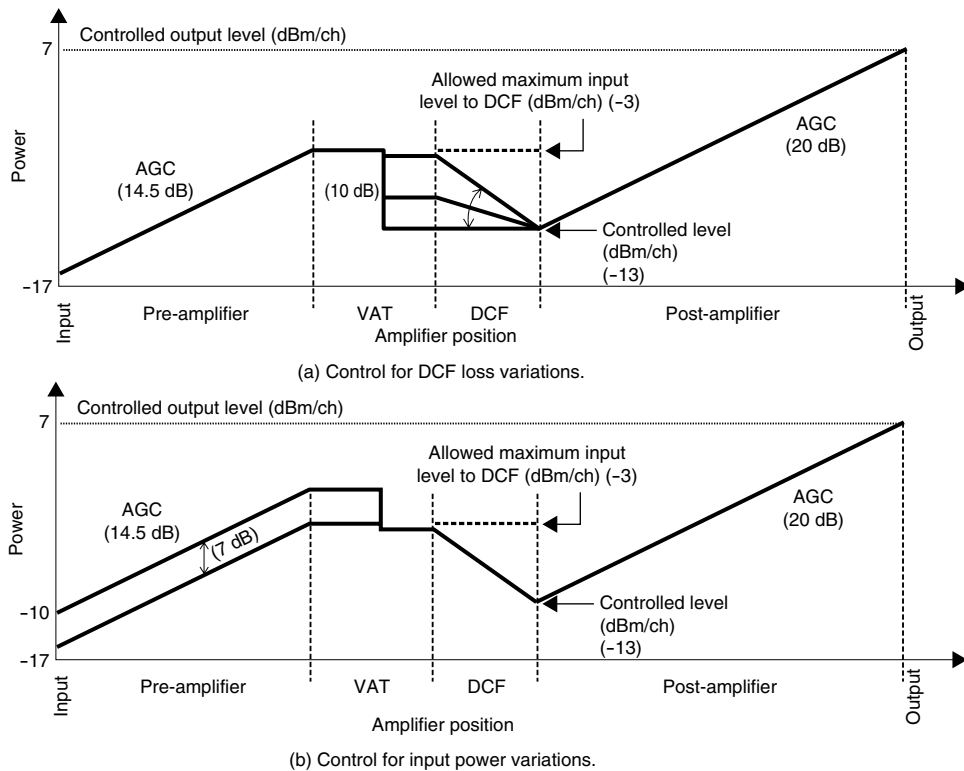


Figure 6 Level diagrams of proposed WDM amplifier.

cluding connector losses (10 dB), which gives -13 dBm/ch. The amplifier therefore realizes per carrier ALC operation by absorbing the variation in DCF loss with an input power of less than -3 dBm/ch. Moreover, if the input power to the pre-amplifier varies by the span-loss variation shown in Figure 6 (b), the mid-attenuator between the pre-amplifier and the DCF always absorbs the variation in signal power.

Figure 7 shows a typical output spectrum for 32-wavelength amplification. The stability of spectral-gain and per carrier grid-to-grid ALC operation is shown in Figure 8. Over a 7 dB input power range (-17 to -10 dBm/ch), the output powers of the 32 wavelengths were controlled to within 7.0 ± 0.6 dBm and no major spectral-gain change was observed. Figure 9 (a) shows the noise figures

of the 32 wavelengths at five points over this power range with compensation for a 9 dB DCF loss and with the OSC demultiplexer loss included. Figure 9 (b) shows the maximum noise figures at these five input powers. Note that even with a 9 dB DCF loss compensation, the maximum noise figure (NF[Max]) at -17 dBm/ch was only 7.2 dB.

Smooth changing of the number of wavelengths (or channels) is an important requirement in a WDM system. Usually, for a simple and cost-effective configuration, the amplifier controls the total output power instead of individually controlling the output powers of each channel. However, the problem with total-power-controlled ALC operation is that the reference changes when the number of channels varies. Scalability for the number of channels is realized by the sequence

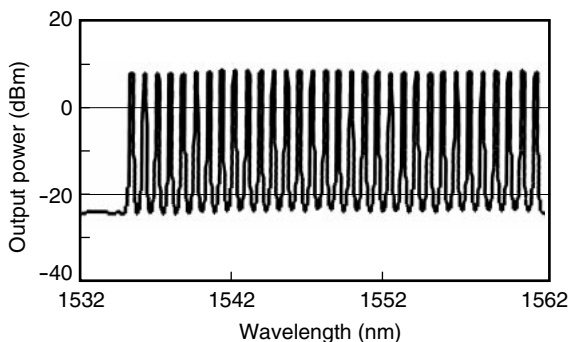


Figure 7
Typical output spectrum for 32 wavelength amplification.

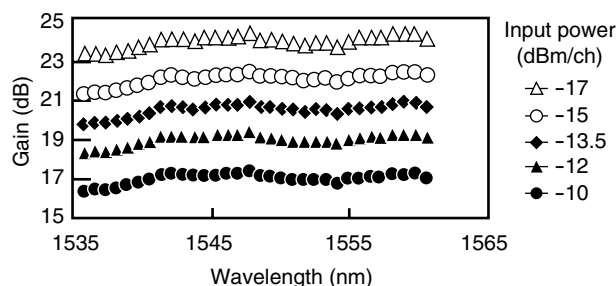


Figure 8
Stability of spectral-gain and per carrier operation with input power variations.

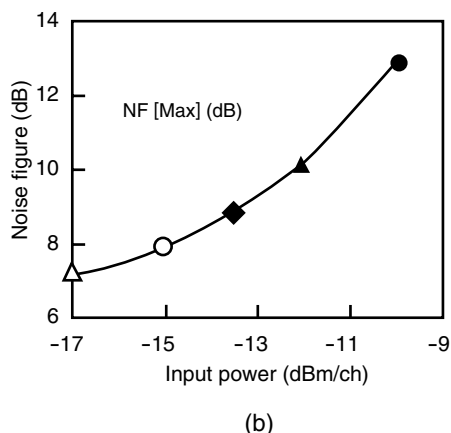
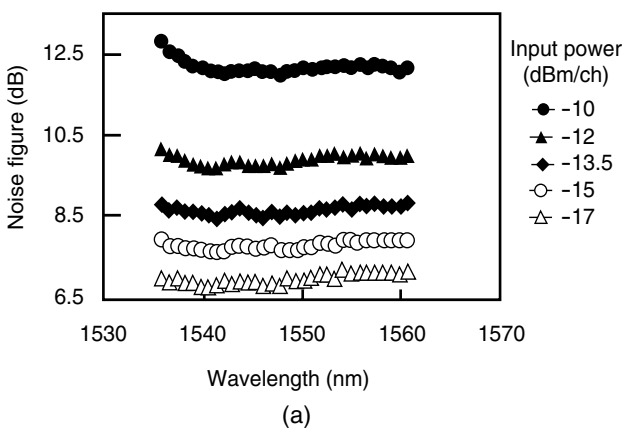


Figure 9
(a) Noise figures of 32 wavelengths for various input powers with a 9 dB DCF loss compensation and the OSC demultiplexer loss included.
(b) Maximums of Figure 9 (a).

described below.⁶⁾ The sequence requires a new function in the OSC instead of extra optical components such as an optical spectrum monitor in the amplifier. A channel upgrade involves changing from ALC operation to AGC operation by freezing the operation of the variable optical attenuator. During AGC operation, the total output power is always equal to the total input power multiplied by a fraction of the net gain, which means that the AGC mode allows the input power to change by channel adding or dropping without affecting surviving channels. In the proposed WDM amplifiers, ALC operation is realized by adjusting the attenuation in the mid-attenuator while each EDF-section operates in AGC mode. Switching between ALC and AGC is easily done by controlling the operation of the mid-attenuator.

Figure 10 shows the channel upgrade sequence. The sequence is performed as follows. 1) First, a kind of network management system (NMS) gives an advance announcement about the channel upgrade to each amplifier through the OSC. The announcement also includes information about the new number of channels. 2) Each amplifier switches its operation mode from ALC to AGC by freezing the operation of the variable

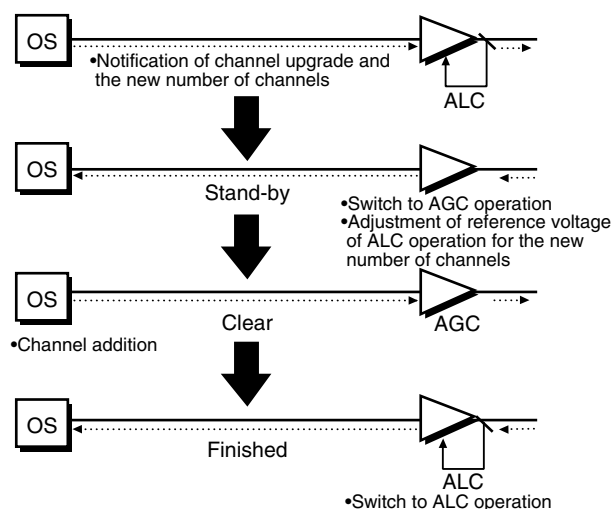


Figure 10
Sequence of channel upgrade through optical supervisory channel.

attenuator and adjusts the reference voltage of ALC operation according to the new number of channels. Then, the amplifiers respond to the NMS by sending a "Stand-by" signal. 3) After receiving "Stand-by" responses from all amplifiers, the NMS smoothly increases the power of the added channel or channels to make the AGC operation follow the increase in input power. The AGC operation allows the input power to be increased without affecting the output power of surviving channels. Then, the NMS instructs each amplifier to return to ALC operation. 4) The amplifiers change to ALC operation based on the new reference voltage, which avoids or minimizes needless transient responses from amplifiers. Finally, the NMS finishes the upgrade process after it receives "Finished" responses from all amplifiers. A channel drop is executed using a similar sequence.

We measured the transient response of one of the surviving channels when the number of channels was increased during AGC operation. In this test we used five wavelengths at input powers that emulated an addition from 16 wavelengths to 32 wavelengths for an input power of -15 dBm per wavelength. **Table 1** shows the input powers of these wavelengths during the test. Wavelengths 1536 nm, 1548 nm, and 1560 nm were set to -8 dBm to emulate the power of five wavelengths each, and wavelength 1554 nm was set to -15 dBm to represent a single wavelength. This gave an equivalent of 16 wavelengths ($5 + 5 + 5 + 1 = 16$). Then, wavelength 1547 nm was changed from less than -30 dBm to -3 dBm to emulate the addition of 16 new wavelengths and the change in wavelength 1554 nm was measured. The output power response of the 1554 nm signal was measured through a narrow bandwidth optical filter when the 1547 nm signal was added. The rise time of the added signal was 5 ms. **Figure 11** shows that the output power deviation of wavelength 1554 nm after the addition was as low as 0.22 dBpp.

We have confirmed the superior performance of these WDM amplifiers by conducting 320 Gb/s

WDM transmissions over a 320 km SMF, achieving a bit error rate of less than 10^{-15} for all channels.

5. Conclusion

We described the novel wide-dynamic-range WDM optical fiber amplifiers we have developed for 32×10 Gb/s SMF transmission systems. These amplifiers operate by automatically compensating for span loss and DC loss variations based on information about the number of wavelengths which is obtained through the OSC. These WDM optical fiber amplifiers realize per carrier ALC operation over a 7 dB input power range. We also described how scalability for the number of wavelengths is achieved using an ALC/AGC switching scheme.

These WDM amplifiers make it possible to fully realize the potential of WDM technology, for example, flexible, scalable, and less-expensive construction of high-capacity transmission systems. Moreover, unlike the new rare-earth doped optically-amplifying fibers, the technologies we have developed that relate to new configurations and

functions do not limit the usable bandwidth. Therefore, those technologies can be applied to any other band within the 40 THz capacity of the transmission fiber with new optically-amplifying fibers.

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Table 1
Input powers during emulation of addition from 16 wavelengths to 32 wavelengths.

Wavelength (nm)	1536	1548	1560	1547 (added)	1554 (measured)
Input power (dBm)	-8	-8	-8	-30 \rightarrow -3	-15

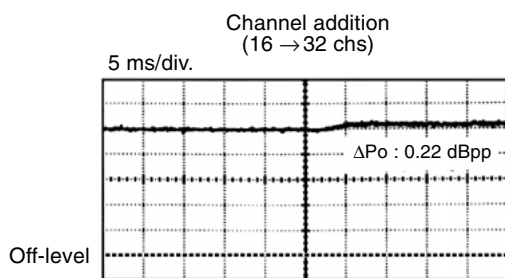


Figure 11
Change in output power of a surviving channel (1554 nm) due to an emulated addition from 16 wavelengths to 32 wavelengths.



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