DWDM TESTING WITH A HIGH-POWER SLICED ASE COMB SOURCE

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Introduction

The trend towards higher capacity in DWDM systems is resulting in dramatic increases in the number of transmitted channels. Up to one hundred 50-GHz spaced channels can be multiplexed across the C-band and the channel count can be increased further by reducing the channel spacing and/or expanding into the L-band [1,2]. As the number of channels continues to increase, the cost of the required bank of transmitter DFB laser diodes increases proportionately. This not only affects the capital costs of the transmission systems, but can also have a major impact on the investment required for equipment necessary for DWDM amplifier and system testing. Typically, the behavior of EDFA and Raman amplifiers are greatly affected by the number of transmitted channels as well as the channel spacing and powers. In addition, nonlinear effects in the transmission fiber such as Raman channel-to-channel power redistribution and four wave mixing (FWM) depend on the parameters of the composite signal. Therefore, proper signal loading is required in order to correctly measure the optical signal-to-noise ratio (OSNR) of transmitted channels in DWDM systems. For some DWDM testing, a reduced set of more powerful channels, having the same composite power as the full complement of wavelengths, can be used. However, larger frequency spacings and higher per channel powers can change the magnitude of nonlinear impairments and the spectral distribution of the OSNR. A simple and affordable comb simulator capable of providing realistic channel loading could simplify the testing of DWDM systems and their components and reduce test equipment costs.

To date, there have been a number of reports of WDM comb sources based on different techniques such as slicing of amplified spontaneous emission (ASE) of erbium-doped fiber (EDF) and

LED luminescence sources [3,4], multi-frequency oscillation of fiber and semiconductor lasers [5,6], and generation of broadband supercontinuum radiation in a fiber fed with ps-pulses from a mode-locked fiber laser [7]. Although a multi-channel source produced by narrow-band ASE slicing is difficult to adopt for high-bit-rate transmission because of unacceptable intensity noise, it can be used as an effective tool for DWDM components and system testing. In some cases, it can be even used for transmission, e.g. in [8] a noise reduction of 15 dB has been demonstrated by amplification of 0.5-nm wide ASE-sliced channels in a highly-saturated semiconductor optical amplifier, allowing 2.5 Gbit/s transmission. The slicing of ASE sources can be achieved by means of Bragg grating chains or Fabry-Perot (FP) filters anchored to the ITU frequency grid. In this paper, we describe the performance parameters of a 50-GHz spaced ASE-sliced comb source and discuss its application to DWDM optical amplifier and system testing.

Comb Source

High power per channel, accurate channel positions and high signal-to-valley extinction ratio are among the most important parameters of the comb source. To achieve optimal performance, fiber-coupled Fabry-Perot filters having a free spectral range (FSR) of 50 GHz were placed between EDF stages, providing an optimal tradeoff between high output power per channel and extinction ratio. The emission spectrum of the source shown in Fig.1 was measured with a spectral resolution of 0.01 nm using an Ando AQ6317B optical spectrum analyzer (OSA). The source provides approximately one hundred ASE peaks in the C-band. The variation of the channel powers across the spectral range from 1529 to 1565 nm is less than ± 1 dB thanks to a gain-flattening filter placed after the first EDF stage. The FP filters have been temperature tuned to match the frequency of one of the central peaks to the ITU frequency of 193.10 THz, corresponding to a wavelength of 1552.52 nm. The filters have a transmission peak temperature sensitivity of - 1.22 GHz/C°. Their temperatures are maintained within an accuracy of ± 0.2 C°, providing long-term stability of the peaks' spectral positions within ± 2 pm. The wavelength deviation of the shortest and longest channels from the ITU grid, resulting from the accumulated inaccuracy of the FSR and the material dispersion of the FP filters, are less than 20 pm. The emission spectrum around three central peaks is shown in Fig. 2. All peaks have an optical linewidth in the range of 36 to 38 pm (FWHM). The channel peak-to-valley extinction ratio, measured with a spectral resolution of 0.01 nm, is approximately 49 dB. The total composite output power of the source is 22 dBm, corresponding to ~ 1.6 mW per channel. The long-term power stability is better than 0.05 dB/day, making repeated reference spectrum recording unnecessary.

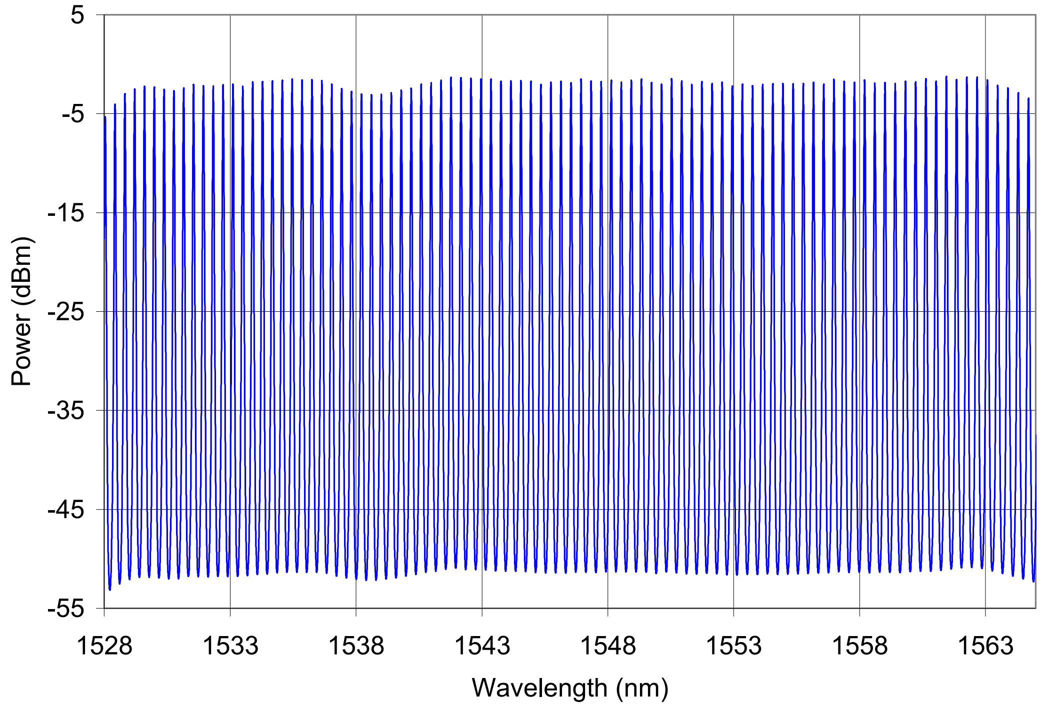


Fig.1. Emission spectrum of the ASE-sliced 50-GHz spaced comb source.

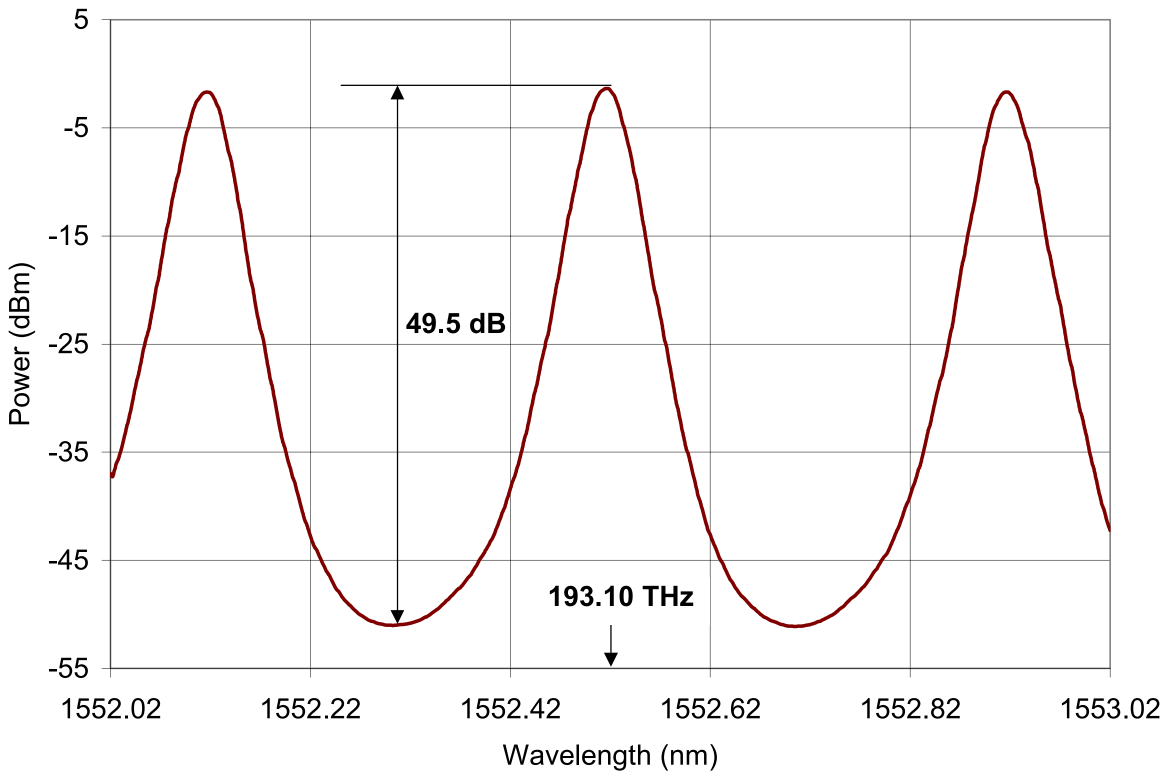


Fig.2. Emission peaks are anchored to ITU grid.

EDFA Testing

The comb source provides an effective means of simulating a DWDM signal for the characterization of the gain and noise figure (NF) of an EDFA. To correctly measure these amplifier parameters, the input signal must represent a condition of full channel loading and its ASE noise, after being amplified in the EDFA, should be well below the EDFA's own ASE noise. Usually, the NF of an optical amplifier can be defined using the simplified formula:

$$NF = P_{ASE\text{-}EDFA}/(h\nu\Delta\nu G) + 1/G ,$$

where $P_{ASE\text{-}EDFA}$ is the integrated amplifier ASE power within bandwidth $\Delta\nu$, $h\nu$ is the photon energy and G is the amplifier gain (all quantities in linear units). The above expression for the NF is valid and yields the real signal-to-noise ratio degradation caused by the amplifier provided the following three conditions are satisfied:

1. The input signal is shot-noise limited
2. The detected signal-ASE beat noise is the dominant cause of the SNR degradation. Other noise contributions such as ASE shot noise and ASE-ASE beat noise are small enough to be neglected.
3. $P_{ASE\text{-}EDFA} >> P_{ASE\text{-}COMB}\, G$, where $P_{ASE\text{-}COMB}$ is the "ASE power" of the comb source (i.e. the power in the valleys mid-way between the comb peaks) at the input of the EDFA.

Usually the second condition is satisfied since, typically, a narrow-band optical filter is used to limit the ASE-ASE beat noise contribution and the signal is strong enough to make the signal-ASE beat noise dominant. To find the requirement on the peak-to-valley extinction ratio of the comb source to satisfy the third condition, consider an EDFA providing amplification of one hundred 50-GHz spaced channels and having composite input and output powers of 0 dBm and 23 dBm, respectively. The output composite ASE power generated by the EDFA can be found from the noise figure formula:

$$P_{ASE\text{-}EDFA} = (NF*G - 1)\, h\nu\Delta\nu$$

Assuming an OSA resolution of 0.02 nm, G = 23dB and NF = 5dB, the amplified ASE power integrated over the OSA bandwidth is $P_{ASE\text{-}EDFA} = (3.16 \cdot 200 - 1) \cdot 6.62\ 10^{-34} \cdot 2\ 10^{14} \cdot 2.5\ 10^{9} = 0.21\ \mu W$ or -36.8 dBm. Rewriting the third condition in logarithmic units and imposing a condition limiting the ASE contribution of the comb source to no more than 5% (or –13dB) of the ASE generated by the EDFA, the acceptable ASE power of the comb source at the EDFA input is:

$$P_{ASE\text{-}COMB} \leq P_{ASE\text{-}EDFA} - G - 13dB = -72.8\ dBm$$

Then, the required peak-to-valley extinction ratio of the comb source at the input of the EDFA is:

$$OSNR_{COMB} = P_{COMB/CH} - P_{ASE\text{-}COMB} = -23dBm - (-72.8\ dBm) = 49.8\ dB,$$

where $P_{COMB/CH}$ is the apparent comb "signal power" per channel (as measured with an OSA resolution of 0.02 nm) at the input of the EDFA.

To meet this requirement, an extra FP filter has been added at the comb source output, increasing $OSNR_{comb}$ to 54 dB as measured with an OSA resolution of 0.02 nm. We have used the comb source to test a DWDM EDFA (MPBC, Model P21F) having a nominal output power of 21 dBm and a flat gain spectrum at a composite input power of 0 dBm. Input and output signal spectra are shown in Fig.3. As can be seen from the amplified spectrum, the valleys between peaks are filled with ASE generated by the EDFA. To graphically illustrate that the ASE seen in the valleys of the amplified spectrum accurately reflects the amplifier's own ASE, an add/drop filter was connected to the output of the comb source, resulting in the 1552.52-nm peak being suppressed by more than 60 dB. The ASE level at the dropped wavelength is thus solely due to the amplifier's ASE and it can be seen that it is similar to the level in the valleys between nearby channels. One can estimate that the contribution of the source ASE amplified by the EDFA is about 16 dB lower than the ASE generated by the EDFA itself and therefore can be neglected. Gain and NF figure spectra measured at three different composite input powers are shown in Fig.4. These measurements can be accomplished with just two scans of an OSA that can track each comb source peak and then calculate the OSNR and Noise Figure spectra. The gain spectrum is flat when the composite signal power is close to the nominal level of 0 dBm. Changing the signal power affects the population inversion of the EDFA and, as a result, creates a positive or negative spectral tilt of the gain. It can be seen that the average noise figure was degraded by ~1 dB when the composite input signal was increased from – 3 dBm to + 3 dBm.

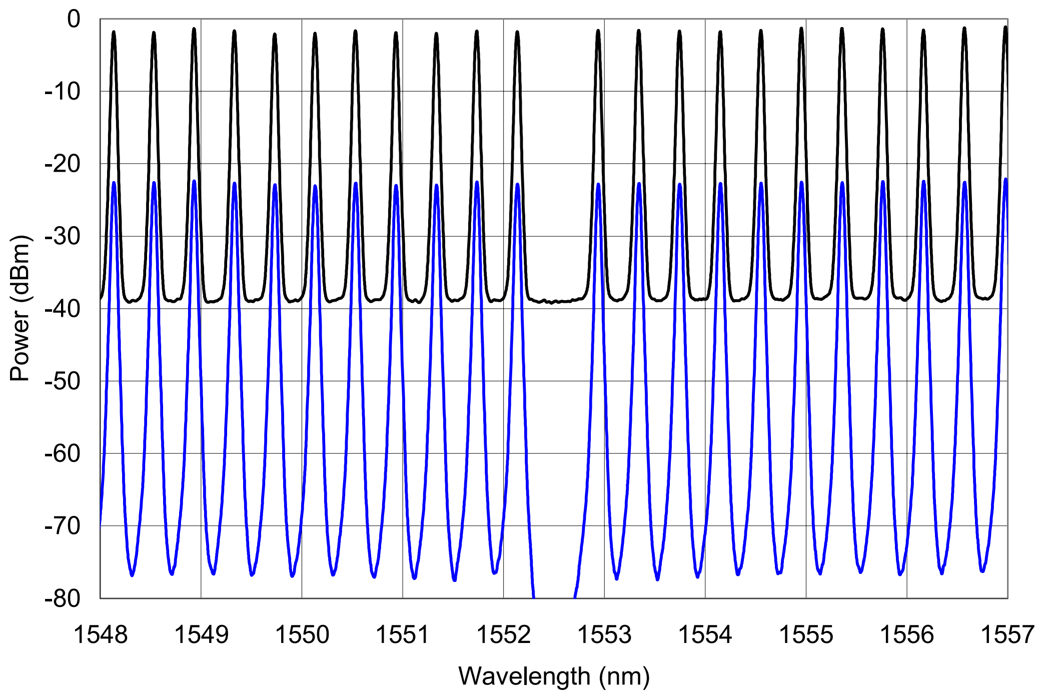


Fig.3. Comb spectra at the input and output of the EDFA measured with an OSA resolution of 0.02 nm.

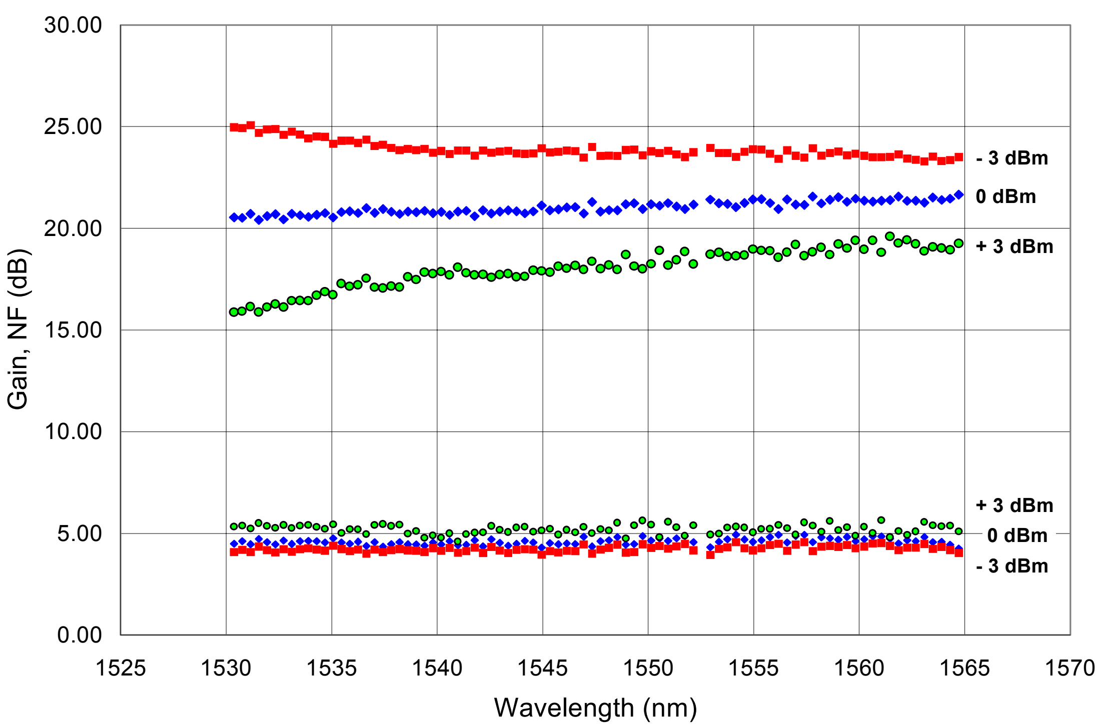


Fig.4. Gain and Noise Figure of EDFA measured at composite input powers of –3, 0 and +3 dBm.

Distributed Raman Amplification

It is known that the Raman effect is responsible for a power redistribution between transmitted WDM channels if the signal launch power is high and the channels are spread across a wide spectral band [9]. Long-wavelength channels experience Raman amplification at the expense of those at shorter wavelengths. Thus, the transmitted channels acquire an additional tilt, where short-wavelength channels are attenuated, while long-wavelength channels are amplified. The comb source can be used to measure this spectral tilt. In addition, the comb source is ideally suited for measuring the Raman gain and signal OSNR spectra.

To illustrate this, we used the fiber link shown in Fig.5. The link consists of two sections of pure silica core fiber (PSCF) separated by a 28-dB optical attenuator. The total attenuation was equivalent to a 255-km length of PSCF.

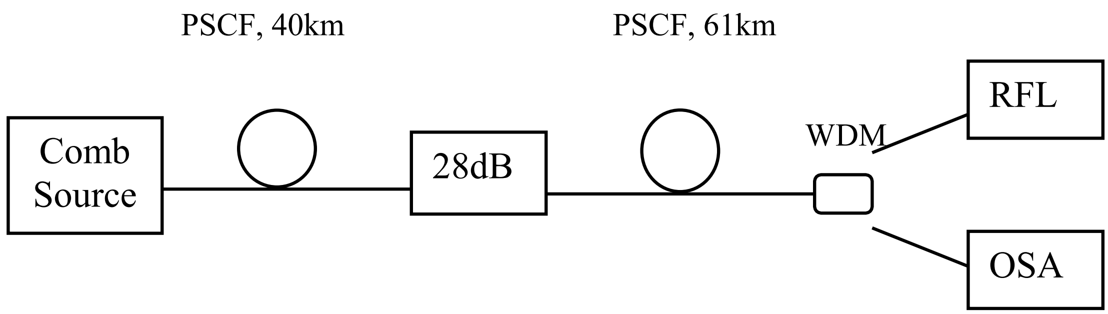


Fig.5. Experimental set-up for testing 255-km PSCF link with Raman amplification.

We first investigated the received DWDM spectrum in the absence of distributed Raman amplification. When the signal power is low, the short-wavelength channels of the C-band experience only slightly higher attenuation than those at the upper end of the band, due to the spectral dependence of the fiber's optical loss governed by Rayleigh scattering. A spectral slope of - 1.2 dB was measured across a 40-nm spectral range when the composite launch power was 0 dBm (Fig.6). It should be noted that a part of this slope was introduced by the attenuator which contributed - 0.5 dB/40 nm. In a full 250-km PSCF link, one can expect a slope of about - 1.5 dB across the C-band. The spectral slope of the attenuation however becomes much steeper when the composite signal power is high. As can be seen from Fig.6, the short-wavelength channels experience much higher loss compared to the long ones. At a composite launch power of 21.8 dBm, a total spectral slope of - 3.8 dB was measured across 40 nm and much of it, ~ 2.6 dB, was due to Raman channel-to-channel power redistribution.

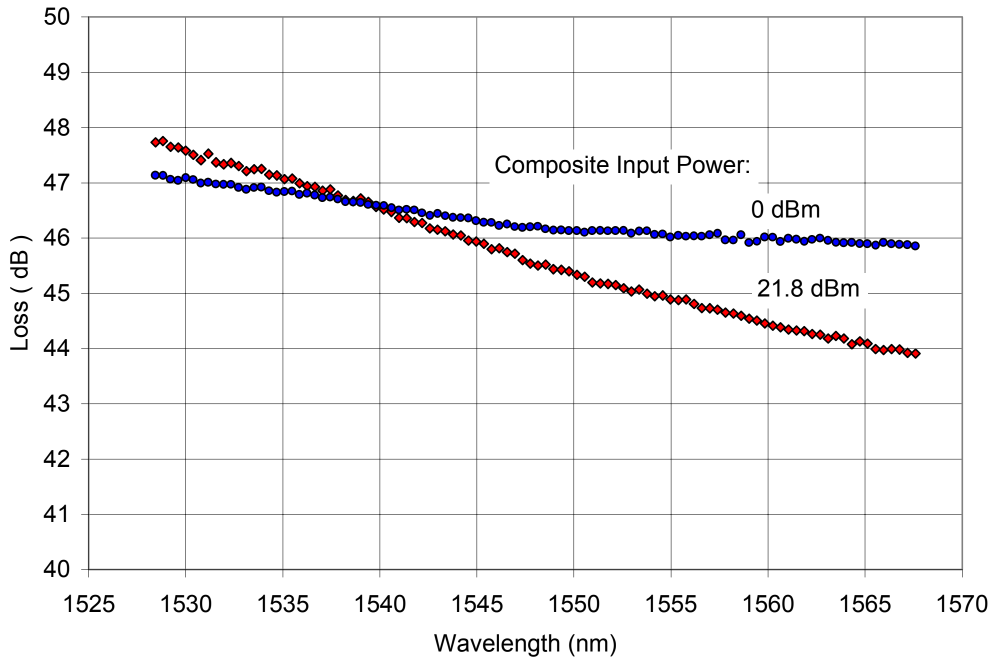


Fig.6. Attenuation of the DWDM signal in a PSCF link measured at two different composite powers.

Distributed Raman amplification was then implemented in the second, 61-km long section of PSCF via first- and third-order Raman pumping schemes. In the case of first-order pumping, a dual-wavelength Raman fiber laser [10] with emission wavelengths of 1427 and 1453 nm was used. The powers were adjusted to compensate the spectral tilt and provide a flat output signal spectrum when the composite signal launch power at the input of the first section of the link was 21.8 dBm. Fig.7 shows a portion of the received optical spectrum, containing a few peaks of the comb in the middle of the C-band, when the Raman pump was turned on and off. Raman ASE noise can clearly be seen in the valleys between the peaks and can be used to measure the signal OSNR and the effective Noise Figure of the distributed Raman amplifier.

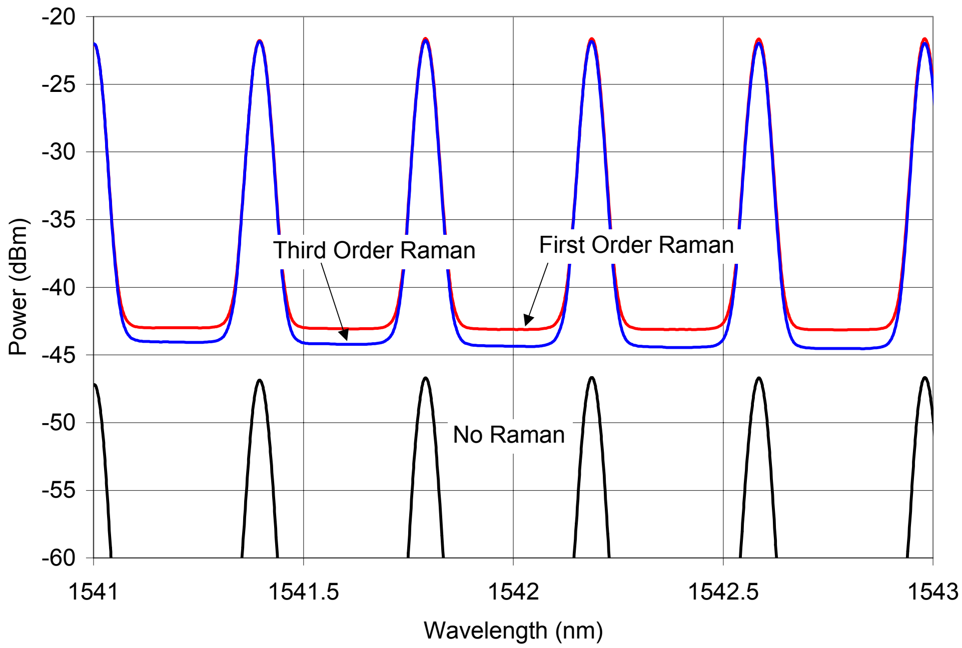


Fig.7. Comb signal spectra measured at the link output when the Raman pump was turned off, and amplified signal when the link was pumped by first- and third-order Raman pumps.

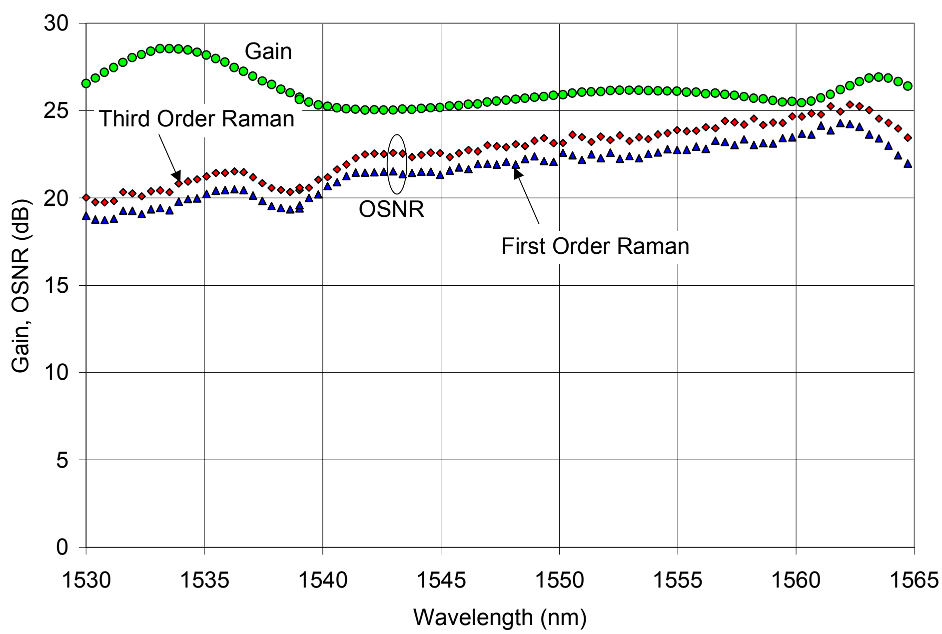


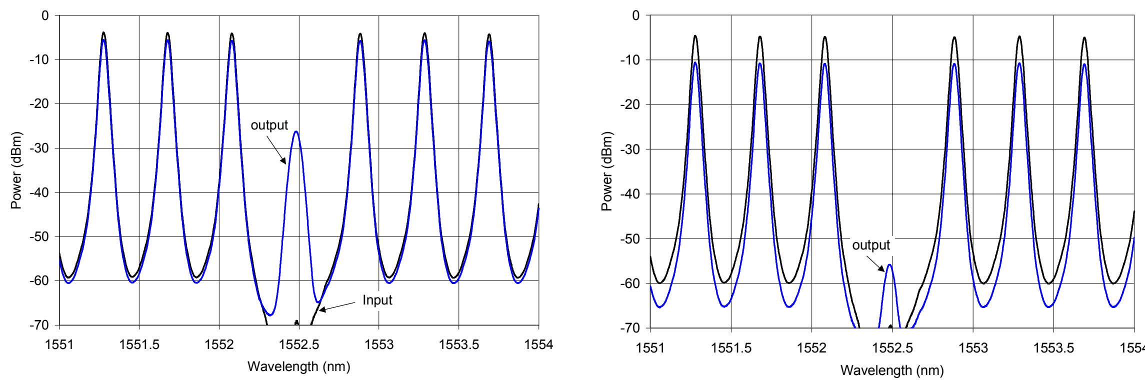
Fig.8. On/off Raman gain spectra and OSNR measured at the output of the link when pumped by the first-and third-order dual-wavelength Raman pumps.

In the case of third-order pumping, a primary pump at 1276 nm was launched into the link together with weak seed light at 1426 nm. The secondary, 1365-nm pump power is developed within the transmission fiber and is in turn converted into power at the final pump wavelengths of 1426 and 1454 nm. The primary pump and the seed powers were adjusted to provide the same Raman on/off gain as in the case of first-order pumping. As can be seen from Fig.7, third-order cascaded Raman pumping provides the same gain but results in less ASE noise. Fig.8 shows the OSNR spectrum of the DWDM comb signal at the output of the link for first- and third-order Raman pumping. An OSNR improvement of ~1.2 dB is seen for third-order pumping. This is ~1 dB smaller than demonstrated in [11] for the case of single-wavelength Raman pumping. The smaller improvement is in part due to the short length of the second section of the link which limited the pump penetration into the fiber span. Also, dual-wavelength first-order pumping itself provides ~ 0.5 dB more improvement than single-wavelength pumping.

In spite of the higher Raman gain provided to the short-wavelength channels, the OSNR is 5 dB worse than for the long-wavelength channels. As we showed earlier, a substantial part of the OSNR tilt (~ 3.8 dB) is due to the channel-to-channel power redistribution and fiber spectral loss. The rest is due to higher Raman ASE noise at the channel wavelengths located closer to the pump. To obtain a flat OSNR spectrum, one might use signal pre-emphasis at the link input or use Raman co-pumping to provide some gain for the short-wavelength part of the DWDM signal.

Four Wave Mixing

When high-power, dense-wavelength-multiplexed channels are transmitted through a low- dispersion fiber, new frequencies can be generated via a nonlinear cross-channel interaction known as four wave mixing [12]. In the case of ITU-grid DWDM, the channels have equal frequency spacing and the products of interacting channels fall at ITU-grid frequencies and thus coincide with transmitted signals. When detected, the signal and the FWM product experience beating, giving rise to broadening of the "one" level of the eye diagram. Even a relatively small FWM product (- 20 dB relative to the signal) can cause a ± 1-dB amplitude fluctuation of the detected signal [13]. The value of the FWM product depends on channel spacing, power per channel, number of channels and the dispersion properties and normalized nonlinear index (n_2/A_{eff}) of the transmission fiber. To determine the actual FWM impairment, one might need to run a bit-error test using a bank of DFB lasers. However, we propose to use the comb source as a tool to predict possible penalties due to the FWM interaction of DWDM channels. At this point, we can only demonstrate the use of the source to qualitatively estimate the effect of FWM, aiming in future to find a quantitative relation between OSNR degradation and actual BER penalties. The add/drop filter discussed earlier was inserted at the output of the source, suppressing the 1552.52-nm peak by more than 60 dB. The dropped peak can be replaced by another signal carrying data or the gap can be used to monitor FWM. Fig.9 shows how the FWM product has grown after propagating in DSF and TrueWave fibers. In DSF fiber, as expected, the FWM process is very efficient because of the perfect phase matching between a large number of interacting channels. After 6 km of fiber, the ratio of the mixing product to the transmitted channel power was measured to be –20 dB and it is obvious that such a fiber cannot be used for DWDM transmission. Instead, non-zero dispersion fibers provide a small amount of dispersion which effectively reduces the phase-matching length over which the channels can interact. As



(a) (b)

Fig.9. Central part of the comb spectra measured at after 6 km of dispersion shifted fiber (a) and 23 km of TrueWave fiber (b). Composite input signal power in both cases was 18 dBm.

a result, the ratio of the FWM product to the transmitted channel power, measured after 23 km of TrueWave fiber, is – 49 dB. As can be seen from these examples, the comb source combined with an add/drop filter can be used to evaluate the effect of FWM and predict OSNR degradation. There are two remaining questions: (a) Does the FWM interaction of an ASE-sliced comb lead to the same OSNR degradation as modulated DWDM signals from a bank of DFB lasers having the same spectral spacing, power and number of channels? and (b) Would the same OSNR degradation result in the same BER penalties? More tests are required to establish a quantitative relationship between the magnitude of the FWM product measured with the comb source and the BER penalties that would be encountered in an actual DWDM transmission system.

Conclusions

A high-power sliced ASE comb source, designed to simulate a full complement of 50 GHz-spaced C-band DWDM channels, has been developed and evaluated as a substitute for a costly bank of DFB lasers for DWDM amplifier and system testing. With its 22-dBm composite output power, high stability, flat spectrum and high peak-to-valley extinction ratio, the comb source has been shown to be ideally suited for measurements of the gain and NF spectra of EDFAs under conditions of full channel loading. It also readily allows measurement of the OSNR evolution in long-haul DWDM systems, including the effect of Raman channel-to-channel power redistribution, the margin improvement provided by distributed Raman amplification and the growth of FWM products. The ease with which these measurements can be performed demonstrates that such a source is both a convenient and a cost-effective replacement for banks of DFB lasers for many test applications.

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