Evaluation of Nonuniform WDM Source Spacing for EDFA Gain Characterization

Shamal Kulkarni, John Medberry, and Kevin L. Lear

***Abstract*—The accuracy of erbium-doped fiber amplifier gain characterization tests has been evaluated using reduced sets of wavelength-division-multiplexing laser sources. Wavelength grids with both uniform and nonuniform wavelength spacing have been evaluated. Experiments show that it is necessary to maintain equal spectral density of source power per region in order to operate at the same saturation/inversion conditions of the amplifier. By doing so, acceptable results were obtained for a laser configuration with 400–800-GHz nonuniform spacing, employing 12 lasers.**

***Index Terms*—Erbium, gain measurement, optical fiber amplifiers, optical hole burning, wavelength-division multiplexing.**

I. Introduction

THE TWO main concerns while building an erbium-doped fiber amplifier (EDFA) test system are that of simulating actual operating conditions of the amplifier and maintaining low system costs. Duplicating the operating conditions of the amplifier as accurately as possible requires the use of a dense wavelength-division-multiplexed (DWDM) signal. A DWDM signal can be implemented using 100-GHz spacing between sources, requiring 64 (or more) lasers, depending on the operating band of the EDFA under test.

Ideally, a fully populated source grid would be used to test the amplifier characteristics under operating conditions. However, due to the high cost of each DWDM laser, it is of interest to minimize the number of lasers required to obtain EDFA gain and noise profiles. A single source is not sufficient to accurately represent the operating conditions of the amplifier, and it can also cause measurement errors, due to spectral-hole burning effects. Reducing the number of sources should not compromise the accuracy of results so a tradeoff between test system cost and test accuracy is required. This letter presents a minimal set of WDM sources that yields comparable C-band EDFA gain and noise profiles to those determined using a fully populated set of sources.

Previous work [1], [2] has shown that the maximum allowable uniform source spacing across the C-band was 400 GHz, requiring 16 sources to span the 1520–1565-nm range. If the number of sources was further reduced to allow 800-GHz spacing across the entire band, the accuracy was unacceptable. Thus, 100-, 200-, and 400-GHz uniform source spacing gave nearly identical results. However, only uniform source spacing was evaluated by these experiments. Accordingly, we report, for the first time, the successful use of nonuniform source spacing. Based on previous work [1], [2], we consider an upper limit on the error (error being defined as the deviation in gain normalized to the 200-GHz uniform spacing gain) as 0.25 dB. Indeed, higher accuracy may be required, depending on the application. While a uniform 800-GHz source spacing falls outside this acceptable range, a novel nonuniform source configuration incorporating spacings as large as 800 GHz was found to be acceptable, as described in this letter.

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II. Setup

A schematic of the equipment used is shown in Fig. 1. The combined WDM signal is fed into a booster EDFA, which may also be bypassed, depending on the signal power required at the input of the EDFA. The sources are modulated and the measurements on the optical spectrum analyzer are gated so that the ASE can be measured independently. The measurements were carried out at input powers ranging from -13 to -17 dBm, where the input power is the power measured at the input of the device under test (DUT). Although all the powers within this range yielded comparable results, only one set of results (for an input power of -15 dBm) have been included here, to avoid complexity of the graphs. The power input to the DUT is set at the required level by the attenuator. Due to power limitations, the tests could not be conducted at higher powers. The DUT, in this case, is a C-band EDFA (Model Number EFA P23) manufactured by MPB Communications, with a pump wavelength of 980 nm, maximum saturated output power of 23 dBm, and no gain-flattening filters. The EDFA was operated at an output power of 20.4 dBm. The noise gain profile (NGP) test method was used for the measurements because the test time is short and it gives a continuous gain spectrum, which is useful for direct comparison of different source configurations. A detailed explanation of the NGP technique can be found in [3].

III. Channel Plan

From our investigation, we determined that only the blue (shorter wavelength) part of the band required a narrower grid spacing, while the red (longer wavelength) part of the band could be covered with a sparsely populated source grid. To evaluate nonuniform source spacing, the wavelength band was divided into two equal regions and different source spacings were applied to each region while maintaining equal source power (ESP). Region I spanned wavelengths approximately from 1527 to 1546 nm, while Region II covered wavelengths

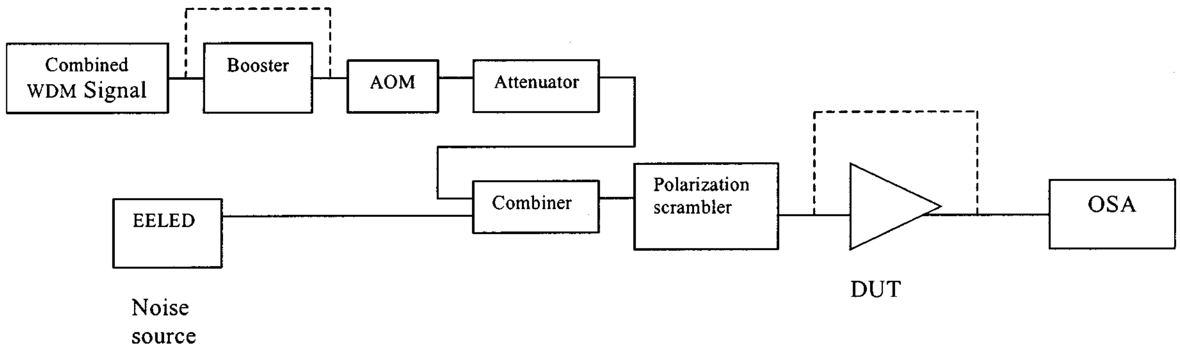

Fig. 1. Experimental setup.

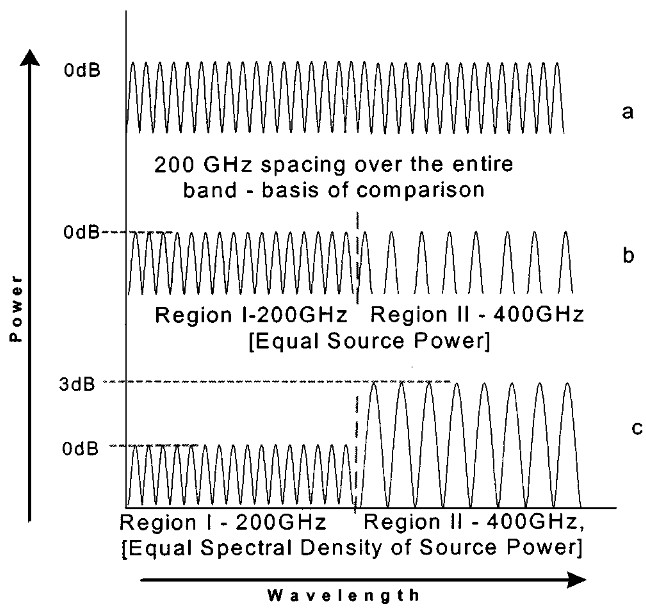

Fig. 2. Schematic of saturating input signals for various power conditions.

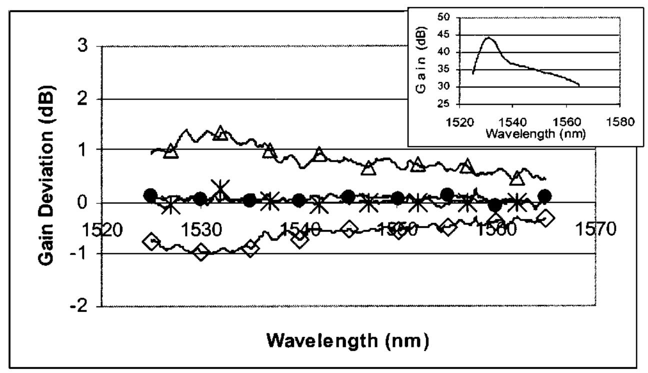

Fig. 3. Gain for 200–400-GHz and 400–200-GHz configurations normalized to gain with 200-GHz uniform source spacing (△ shows 400–200 GHz with ESP, ◇ shows 200–400 GHz with ESP, ⋆ shows 400–200 GHz with ESDSP; ● shows 200–400 GHz with ESDSP). Inset: Typical gain curve for the DUT.

approximately from 1546 to 1565 nm. As an example, in one configuration, 200-GHz spacing is applied to Region I and 400-GHz spacing to Region II, with each source set to the same peak power. This spacing would then be referred to as a 200–400-GHz configuration. However, simply using a less dense grid in either wavelength region is insufficient because this results in a gain tilt of more than 1 dB, due to insufficient gain saturation.

A previous approach [1] to using a reduced set of sources implemented an iterative method to characterize the gain of the EDFA. Our observation of the same gain and ASE for a fully populated set and a reduced source set is consistent with our assumption that the same inversion level is achieved [1]. An indepth investigation into the matter revealed a way to achieve the same gain (as a fully populated source set) without the use of multiple iterations. This is done by maintaining equal spectral density of source power (ESDSP). Fig. 2(b) illustrates a schematic of the applied signal with equal source power (ESP). Fig. 2(c) illustrates a schematic of the applied signal with ESDSP, where the peak power of the sources is maintained equal within a region. An important point to note here is that although the peak power of the lasers in the sparsely populated region is increased for ESDSP, the total input power to the DUT is still maintained constant (i.e., -15 dBm for the results in this letter). Fig. 3 illustrates some results with both power conditions. The desired response would be flat with a minimal excursion.

IV. Measurments and Results

Applying the condition of ESDSP yields results that are very close to the ideal. Several configurations were tested with this condition, in an effort to arrive at the minimal reduced set of sources. Of these, the results for 200–400 GHz and 400–200 GHz using both power conditions are compared in Fig. 3. Results for 400–800 GHz (employing 12 lasers) are shown in Fig. 4. In each chart, the vertical axis represents the deviation of the gain from the 200-GHz gain. Table I gives a summary (channel spacing, number of lasers used and the deviation of gain from the 200-GHz gain) of each configuration tested using ESDSP. Among the configurations that employed ESDSP, maximum deviation from the ideal is found to be approximately 0.25 dB. In order to maintain the same inversion level as a fully populated set, it is necessary to conserve the photon number across the band. The change in photon number caused by using ESDSP is approximately 0.1%, or equivalently, 0.043 dB which is negligible.

In order to correctly understand the response seen, it is qualitatively useful to have an intuitive model for the spectral response of the gain as a function of a single saturating input signal. To evaluate this, we refer to a series of measurements

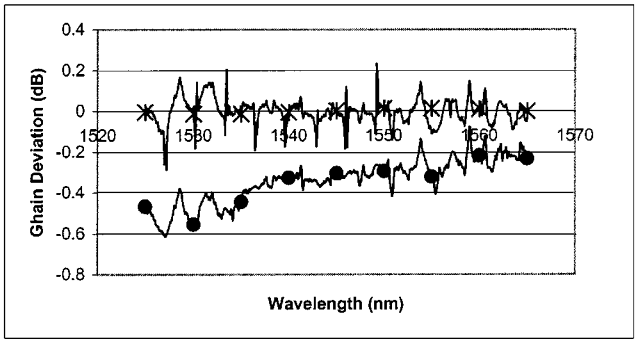

Fig. 4. Gain for additional reduced set configurations, normalized to gain with 200-GHz uniform source spacing (● shows 400–800 GHz with ESP, $\star$ shows 400–800 GHz with ESDSP).

TABLE I
SUMMARY OF RESULTS FOR VARIOUS CONFIGURATIONS USING EQUAL SPECTRAL DENSITY OF SOURCE POWER

Channel spacing (GHz)	Number of lasers	Maximum Deviation in Gain	Standard Deviation in Gain	Average Gain Deviation
150-300	31	0.25dB	0.14 dB	-0.05 dB
300-150	31	0.20dB	0.21 dB	0.049 dB
200-400	24	0.25dB	0.05 dB	0.07 dB
400-200	24	0.25dB	0.05 dB	0.01 dB
400-800	12	0.25dB	0.21 dB	-0.01 dB

made with a single source [4], [5]. Together, these two references can be used to characterize the locations and sizes of the spectral holes in the C-Band. According to [4], the width of the spectral hole varies from 3–8 nm, with the width of the hole increasing with longer wavelengths. The results presented in Table I are in accordance with the results of [4] and [5]. Based on the several configurations tested, the upper limit on nonuniform source spacing for the wavelength band under consideration, using two regions, is 400–800 GHz. Increasing the spacing beyond this called for a compromise in the accuracy of results. The 400–800 GHz source spacing scheme is equivalent to 3-nm spacing on the blue end of the wavelength band and approximately 6-nm spacing on the red end of the wavelength band. These spacings are very close to the spectral hole widths reported in [4] and [5]. In order to keep the spectral hole burning effect to a minimum with sufficiently narrow source spacing while keeping system costs low, the 400–800 GHz configuration offers a well-balanced solution, requiring a total of only 12 lasers.

V. CONCLUSION

The spectral hole burning effects on the gain and ASE spectrum in the shorter wavelength region [4] indicate that certain minimum wavelength spacing is required between sources. On the other hand, the width of the spectral hole burning effects toward the red end of the gain spectrum shows that the source spacing can be quite wide. Together, these results require a spacing restriction that varies with the degree of line broadening. Further, the laser peak power and source spacing should be considered together so as to maintain spectral density of source power across both regions. This allows the use of a reduced set of sources, which is found to be significantly less than the previously estimated required number of sources.

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