<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Transmission of optical communication signals by distributed parametric amplification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Kalogerakis, G; Wong, KKY; Marhic, ME; Kazovsky, LG</td>
</tr>
<tr>
<td><strong>Issued Date</strong></td>
<td>2005</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10722/54054">http://hdl.handle.net/10722/54054</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>©2005 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.; This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.</td>
</tr>
</tbody>
</table>
Transmission of optical communication signals by distributed parametric amplification

G. Kalogerakis, K. K. Y. Wong, M. E. Marhic, and L. G. Kazovsky
Department of Electrical Engineering, Stanford University, 058 Packard Building, Stanford, CA 94305, USA
Phone: +1-650-724-3409, Fax: +1-650-723-9251, Email: gkaloger@stanford.edu

Abstract: We have demonstrated, for the first time to our knowledge, distributed parametric amplification, i.e. amplification of 10-Gb/s communication signals along a 75-km transmission fiber by using a co-propagating pump with only 66.5 mW of power.

© 2004 Optical Society of America
OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.2330) Fiber optics communications; (190.4370) Nonlinear optics, fibers

1. Introduction

Distributed parametric amplification has been investigated in the past as a detrimental effect, as strong carriers can amplify in transmission fibers the ASE generated by EDFAs used to amplify signals between fiber spans. This has been done for one-pump [1], [2] and two-pump [3] parametric amplification. Here we investigate, for the first time to our knowledge, a possibly useful application of distributed parametric amplification (DPA), namely amplification of communication signals along a transmission fiber by using a co-propagating pump.

2. Theory

Compared to distributed Raman amplification (DRA), DPA has the advantage of requiring only about 1/3 the pump power for DRA to obtain the same gain. This is attractive, as the power levels required for DRA have raised safety and reliability concerns. In addition DPA is free from double Rayleigh scattering, which is a concern in DRA.

Because of the large length of transmission spans (generally > 40 km) the pump power \( P_0 \) required to make up for fiber loss is relatively modest, of the order of 100 mW. This implies that the gain bandwidth will be fairly small, at best of the order of 10 nm. Hence DPA will not compete with methods providing much larger bandwidths, such as DRA, tellurite EDFAs, etc. On the other hand DPA may be a useful supplement for these other techniques: for example it could be used for transmission near 1300 nm in a system using standard singlemode fiber (SMF) primarily for transmission in the C-band.

Fig. 1 shows theoretical gain spectra for one- and two-pump DPAs using 70 km of DSF, with the following parameters: loss \( \alpha = 0.2 \text{ dB/km} \), \( \beta_i = -1.0 \times 10^{-35} \text{ m}^{-1} \text{s}^4 \); zero-dispersion wavelength \( \lambda_0 = 1550 \text{ nm} \); dispersion slope \( D_4 = 0.07 \text{ ps}/(\text{nm km}) \); nonlinearity coefficient \( \gamma = 2 \text{ W}^{-1} \text{ km}^{-1} \); total input pump power \( P_0 = 100 \text{ mW} \).

![Theoretical DPA gain spectra](image)

Fig. 1 Theoretical DPA gain spectra. (a) One pump, at \( \lambda_1 = \lambda_0 = 1550 \text{ nm} \);
(b) Two pumps, at \( \lambda_1 = 1530.44 \text{ nm} \) and \( \lambda_2 = 1570 \text{ nm} \).

The gain shapes of Fig. 1 are quite sensitive to the choice of the pump wavelength(s); this is particularly true for Fig. 1(b), for which decreasing \( \lambda_1 \) by 0.01 nm leads to a drop of the center of the spectrum by about 5 dB. This high sensitivity is due to the fact that we have assumed that \( \lambda_0 \) is constant along the fiber. In real fibers, however, \( \lambda_0 \)
varies randomly along the fiber length, with a standard deviation \( \sigma_0 \) of the order of 1 nm. Then it is clear that the gain spectrum cannot be affected by changes in \( \lambda_0 \) much smaller than \( \sigma_0 \). This has been verified experimentally in Ref. [3], where it was found that a 2.5 nm change in \( \lambda_0 \) was required in order to obtain a drop in gain of 5 dB. Hence the gain shape in real fibers, while not exactly predictable by the theory for uniform fibers, should be relatively insensitive to pump wavelength(s). \( \lambda_0 \) variations can also help to obtain a flat-topped gain spectrum, as indicated by the results of Ref. [3]. If needed, gain flattening could be implemented by means of a filter at the fiber output. This filter could also remove the residual pump power, and the idler(s). Fig. 1 indicates that a signal gain bandwidth of the order of 10 nm could be available with either type of DPA with suitable gain flattening.

3. Experiment

The experimental set-up is shown in Fig. 2. The transmission fiber consists of three 25 km DSF spools with average zero-dispersion wavelengths \( \lambda_0 \) of about 1550 nm. The dispersion slope \( D_s \) is 0.07 ps/(nm\(^2\) km) and \( \gamma = 2 \text{ W}^{-1}\text{ km}^{-1} \). The fiber attenuation is about 0.207 dB/km, while the input power is 15.53 dB total loss. A tunable laser source, TLS4, set at \( \lambda_p = 1551.13 \text{ nm} \) serves as the pump source. The CW pump is phase-modulated by two phase modulators in cascade, PM1 and PM2, in order to suppress Stimulated Brillouin Scattering (SBS). Both of them are driven by a 2.5 Gb/s pseudo-random bit sequence (PRBS) [4].

![Fig. 2. Distributed OPA experimental set-up.](image)

Polarization controllers PC1 and PC2 align the SOP of the pump with PM1 and PM2, respectively. The pump is then amplified to the desired power level by a C-band EDFA (EDFA1) and filtered by a 1.3 nm tunable bandpass filter (TBF1) to reduce the ASE noise of EDFA1. Three other tunable laser sources, TLS1, TLS2, and TLS3, tuned at 1549.14, 1549.46, and 1549.76 nm, respectively, serve as signal sources. They are modulated by 10 Gb/s NRZ 2\(^{23} \)–1 PRBS as shown in Fig. 2; they are also used to measure the DPA gain. Maximum OPA gain is achieved by aligning the SOPs of signals and pump by PC3, PC5, and PC8. Signals and pump are then combined by a 3-dB coupler, and enter the DSF. The signals input power into the DSF is maintained below \(-18 \text{ dBm} \) while the input pump power is 18.23 dBm (66.5 mW). This ensures that the pump is undepleted, and that low signals-related nonlinear effects would be generated (e.g. XGM, FWM). The output spectrum of the DSF is observed with an optical spectrum analyzer (OSA). Tunable bandpass filter TBF2 selects the desired signal wavelength before detection by the O/E converter.

4. Results and Discussion

We first removed TBF1 in order to inject a broad EDFA ASE spectrum into the DPA. The shape of the ASE spectrum at the output of the DPA then provides an indication of the DPA gain spectrum. The experimental data for the amplified ASE spectrum is shown in Fig. 3(a). Its shape shows a 10-dB bandwidth of about 2 nm on each side of the pump, which can be used for amplifying transmission signals. The gain bandwidth is smaller than expected from theory (Fig.1), which may be due to substantial longitudinal variations of \( \lambda_0 \) in this three-segment link.

We then inserted TBF1 to efficiently suppress EDFA ASE, and turned on the signals. The power of channels 1, 2, and 3 at the DSF input was \(-18.74 \), \(-20.71 \), and \(-20 \text{ dBm} \), respectively. The corresponding on-off signal gains
were 14.4, 16.9, and 16.5 dB, as shown in Fig. 3(b). The gain is sufficient to compensate the transmission loss of the 75 km DSF (15.52 dB).

The amplified signal at 1549.14 nm was then selected by TBF2, and detected for three different cases: (i) when just channel 1 was ON, (ii) channels 1 and 3 were ON, (iii) all three channels were ON. The eye patterns were displayed on an oscilloscope. Examples are shown in Fig. 4(a); the clear opening indicates the high quality of the received signal. Bit error rate (BER) was also measured by varying the received power by means of VOA1. BER plots for the three cases discussed above are shown in Fig. 4(b), together with a reference plot for the transmitter and receiver back-to-back (only channel 1 ON, and connected to the receiver bypassing the DSF). It can be seen that the insertion of the DPA leads to a power penalty of the order of 1.2 dB (cases (i), and (ii)), and 2.1 dB (case (iii)).

5. Conclusion
We have demonstrated, for the first time to our knowledge, distributed parametric amplification (DPA), namely amplification of 10-Gb/s communication signals along a 75-km transmission fiber by using a co-propagating pump with only 66.5 mW of pump power. This provides a novel means of signal amplification in communication networks, which may find practical applications for single- or multi-channel systems.

References