Nonlinear wave mixing and induced gratings in erbium-doped fiber amplifiers

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We present a study of nonlinear wave mixing in erbium-doped fiber amplifiers. Wave mixing is demonstrated in dynamic gain gratings induced by counterpropagating beams from a diode laser.

Erbium-doped fiber amplifiers (EDFA's) have had, in a short period of time, a great effect on the field of optical communications.[1] The gain in EDFA's also creates the opportunity to produce strong optical nonlinearities in fibers. In this Letter we present what we believe to be a first study toward understanding the use of the active EDFA for wave mixing. Here gratings induced in the gain are considered as a means to produce strong coupling effects, as was previously demonstrated for other gain media such as semiconductor amplifiers,[2] semiconductor lasers,[3] and dyes.[4,5] Wave mixing in EDFA's may have significant applications. A recent study,[6] for example, brought up the possibility of the use of such gratings as filters.

Because of the slow response time of the EDFA gain,[7] it is possible to build up any wave-mixing scheme by the basic two-wave mixing process (as in the case of the photorefractive effect[8]). Two counterpropagating (or copropagating) beams, 1 and 2 (see Fig. 1), produce a gain grating that is due to the perturbation of the gain by their interference pattern. Thus the two beams must be mutually coherent, and the difference in their frequencies must be smaller than the reciprocal time response of the gain medium. The induced gain grating affects the writing beams themselves (in the two-wave mixing case) or, in the four-wave mixing case, affects a third signal beam, which need not be coherent with the writing beams and can originate from a different laser.

We can understand two-wave mixing by considering the coupled-wave equation. We start with the nonlinear susceptibility, which is taken to be[4,5,9,10] $\chi = \chi_0/(1 + I/I_S)$, where I is the local light intensity and I_S is the saturation intensity. The fields of two counterpropagating beams are $\overline{E}_1 = \overline{A}_1 \exp[i(k_1 z - \omega_1 t)]$ and $\overline{E}_2 = \overline{A}_2 \exp[i(-k_2 z - \omega_2 t)]$, and their interference gives $I = (I_1 + I_2) + \{A_1 A_2^* \exp[i(k_1 + k_2)z]\exp[i(\omega_2 - \omega_1)t] + \text{c.c.}\}$, where $I_i = |A_i|^2$ and c.c. stands for complex conjugate.

In order to simplify the expressions and obtain a clear understanding of the wave mixing, we assume that the interfering beams do not heavily saturate the gain ($I \ll I_S$). (The general case is treated elsewhere.[10]) In the present two-wave mixing experiment, $\omega_1 = \omega_2$. The coupled-wave equation can be easily obtained[11] for $A_1(z,t)$ and $A_2(z,t)$:

$$\frac{\mathrm{d}A_1}{\mathrm{d}z} = g\left(1 - \frac{\langle I_1 + I_2\rangle}{I_S}\right)A_1 - g\,\frac{\langle A_1 A_2^*\rangle}{I_S}\,A_2\,, \tag{1a}$$

$$\frac{\mathrm{d}A_2}{\mathrm{d}z} = -g\left(1 - \frac{\langle I_1 + I_2\rangle}{I_S}\right)A_2 + g\,\frac{\langle A_1^* A_2\rangle}{I_S}\,A_1\,, \tag{1b}$$

where $g = k\chi_0/2$. The angle brackets indicate the time average of the enclosed term over the characteristic response time of the gain dynamics τ, which is of the order of 1–10 ms. For modulation frequency $\nu_{\text{mod}} \ll 1/\tau$, this average approaches the instantaneous value and experiences the full modulation; whereas, at the other limit, $\nu_{\text{mod}} \gg 1/\tau$, such terms have a constant value corresponding to averaging over the modulation. The two terms over the denominator I_S represent the effects of saturation. The

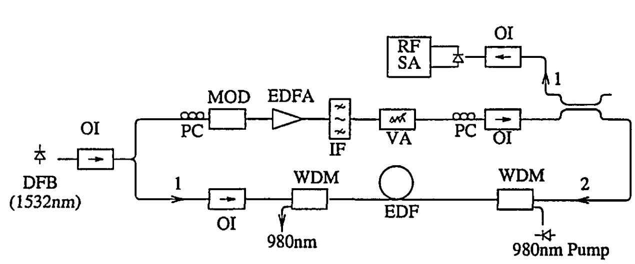

Fig. 1. Experimental setup. DFB, distributed-feedback diode laser; OI's, optical isolators; PC's, polarization controllers; MOD, lithium niobate modulator; IF, interference filter; VA, variable attenuator; RFSA, rf spectrum analyzer; WDM's, wavelength-division multiplexers for 980 and 1550 nm; EDF, erbium-doped fiber under test.

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term proportional to $\langle I_i + I_j \rangle$ arises from the saturation induced by the intensity of each beam independently and is nonzero even in the presence of only one beam. The term proportional to $\langle A_i A_j^* \rangle A_j$ arises from the gain grating formed by the interference of the two beams with each other.

Since the wavelengths of our beams are near the gain peak, χ_0 and g are almost real and positive. A positive g in Eqs. (1) represents amplification, whereas a negative value signifies absorption. In pure phase gratings with imaginary g (as in the local Kerr-like effect), the optical phase of the added reflection from the coupling is 90°, and there is no amplification. In nonlocal phase gratings (as in the photorefractive effect) the nonlocality adds another 90° phase for one of the beams and −90° for the other. This effectively gives a total phase shift of 180° and thus depletion for one beam, whereas the second beam experiences a phase shift of 0° and thus amplification.

Returning to our case, the positive g means that the increment that is due to propagation through the erbium-doped fiber is in phase and the beams are amplified. The second term in each of the coupled-wave equations [Eqs. (1)] represents a component with a change of 180° in the optical phase and corresponds to the gain depletion resulting from saturation. The third term, which represents the reflectivity of the grating induced by the interference between the two beams, also experiences a 180° change in optical phase and thus also represents a depletion of the transmitted beam 1 at the time when beam 2 is on.

In our two-wave mixing experiment the output of a 1532-nm distributed-feedback laser was coupled into fiber and divided (see Fig. 1), and the two beams, denoted 1 and 2, were counterpropagated in 0.97 m of erbium-doped fiber having an aluminogermanosilicate core with an erbium concentration of 2500 parts in 10^6, a diameter of 2.5 μm, and a numerical aperture of 0.33. The powers of beams 1 and 2 were −4 and −8 dBm, respectively, and the power of the 980-nm pump beam was 40 mW. We modulated the intensity of beam 2 on and off to distinguish the reflected beam from the transmitted beam, 1. We varied the modulation frequency from 100 Hz to 20 MHz to distinguish between temporal modulation of the gain saturation and reflections from the induced grating. An EDFA was used for beam 2 to compensate for the loss experienced by this beam that was due to transmission through the modulator and other components.

We detected two-wave mixing by modulating beam 2 and comparing the modulated intensity of transmitted beam 1 emerging at $z = L$ with the input intensity of modulated beam 2 at $z = L$, where beam 1 enters the erbium-doped fiber at $z = 0$ and L is the length of the erbium-doped fiber. The modulated signal that is detected can arise from both the saturation and grating reflection terms in the coupled-wave equations, and the role played by these two terms depends on the modulation frequency ν_{mod} and on the mutual coherence, or lack of it, between the two beams. If the two beams are coherent, then, for slow modulation, i.e., $\nu_{\text{mod}} \ll 1/\tau$, the intensity detected at frequency ν_{mod} results from both terms; i.e., $\langle I_2 \rangle$ and $\langle A_1 A_2^* \rangle$ are essentially equal to their instantaneous values. But for fast modulation, i.e., $\nu_{\text{mod}} \gg 1/\tau$, the gain saturation cannot follow the modulation of I_2, and the term proportional to $g\langle I_i + I_j \rangle$ makes no contribution to the modulated signal. However, the interference term $\langle A_1 A_2^* \rangle A_2$ is proportional to A_2, which is modulated; this interference term will therefore contribute to the modulated signal even for $\nu_{\text{mod}} \gg 1/\tau$. In this case the signal at the modulation frequency results purely from reflection from the grating. If the two beams are incoherent, then for slow modulation the only contribution comes from the saturation term, whereas for fast modulation both terms disappear.

For the simplifying assumption $A_2 \gg A_1$, in which the modulation is applied to A_2, there is a simple solution to Eqs. (1) that illustrates these points:

$$\begin{aligned} A_1(z = L) &= A_1(z = 0)\exp(gL) \\ &\quad \times \exp(-qgL\langle I_2 \rangle / I_S)\exp[-pgL\delta I_2(t)/I_S] \\ &\approx A_1(z = 0)\exp(gL) \\ &\quad \times \exp(-qgL\langle I_2 \rangle / I_S)[1 - pgL\delta I_2(t)/I_S]. \end{aligned} \tag{2}$$

Here $\delta I_2(t)$ describes the intensity modulation of I_2. The indices p and q depend on the modulation regime and on the mutual coherence of beams 1 and 2; $q = 1$ for fast modulation and $q = 0$ for slow modulation, $p = 2$ for the case of slow modulation and mutual coherence of the two beams, $p = 1$ for fast modulation and mutual coherence as well as for slow modulation and incoherent beams; and $p = 0$ for fast modulation if the two beams are incoherent. $A_1(z = L)$ will be modulated only if $p \neq 0$. For the case of fast modulation and mutual coherence of the two beams, the modulation results exclusively from grating reflections. The approximation of linearizing the third exponential is valid for small modulation, $gL\delta I_2(t)/I_S \ll 1$, and permits explicit separation of the modulated and unmodulated components of the signal.

Figure 2 shows the data for measurements of the relative power of the modulated part of beam 1 as a function of frequency. The modulated power is large at low frequencies ($\nu_{\text{mod}} < 2$ kHz), where, in addition to the power reflected by the grating, we are also detecting the effects of temporal modulation of the saturation. For $\nu_{\text{mod}} > 30$ kHz, the detected synchronous power is at a lower level, and it is independent of frequency. At intermediate frequencies the temporal modulation of the saturation is still dominant, but it rolls off at a rate close to 3 dB/octave, as expected. As predicted by the coupled-wave model, the value of reflected power is lower in the high-frequency regime, in which only the grating reflection term contributes to the synchronous signal, than it is at low frequency, where both saturation terms contribute. Such measurements of the frequency dependence of the modulated signal in the transition region between the high- and low-modulation-frequency regimes provides a means to probe and study the gain dynamics of EDFA's.

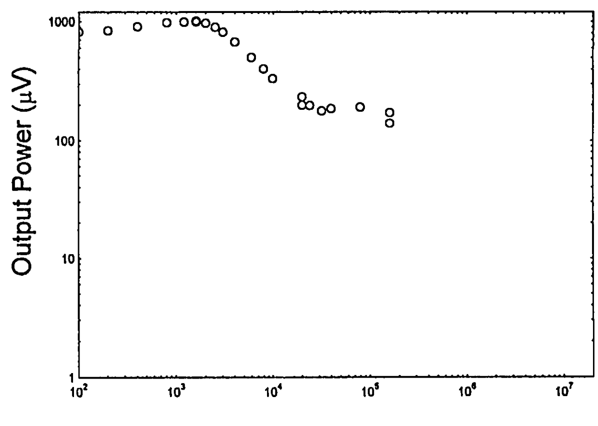

Fig. 2. Synchronous signal as a function of ν_{mod} corresponding to two-wave mixing of the mutually coherent beams.

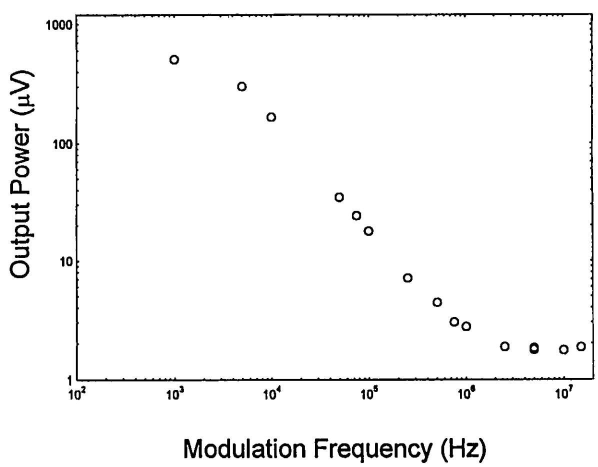

Fig. 3. Synchronous signal as a function of ν_{mod} when the signal line includes a 4.86-km length of single-mode fiber.

We have also looked at the phase of the synchronous component detected for beam 1 relative to that of the modulation of beam 2, and, as predicted by the coupled-wave equations, we find a 180° phase change in both the low- and high-modulation frequency regimes as well as between them.

We repeated this experiment (Fig. 3), placing a 4.86-km length of fiber in the signal leg to remove the mutual coherence of beams 1 and 2. We see the low-frequency temporal modulation of saturation and its 3-dB/octave roll-off, which continues to higher frequencies and lower levels than for the coherent case, until eventually it is dominated, at very low levels, by spurious reflections, and we see no contribution from grating reflection. Thus, as expected, without mutual coherence we do not observe reflection from the grating.

Four-wave mixing results if, in addition to beams 1 and 2, a third input, beam 3, is present that copropagate with beam 2 and with a wave vector sufficiently close to those of the grating writing beams. Then a fourth beam, 4, will be generated by a reflection of beam 3 from the grating. In measurements of four-wave mixing with similar experimental parameters for the fiber and grating writing beams and a weak signal, we observed reflectivities of 6% and a filter bandwidth of 110 MHz.[12] The coupled-wave equations describing the four-wave mixing[11] indicate that the wavelength for peak reflectivity of the grating reflectivity can be controlled dynamically by adjustment of the wavelength of the writing beams. Similarly, the bandwidth and reflectivity can be controlled by adjustment of the power of the gain pumping beam or of the grating writing beams. The reflectivity and bandwidth can also be controlled by appropriate selection of the erbium doping level and waveguide characteristics of the EDFA.

We want to point out the great potential of such gratings for use as controllable filters, the parameters of which can be changed in real time. Such gratings might also be used to generate distributed-feedback or distributed-Bragg-reflector lasers.

In conclusion, we have reported on two- and four-wave mixing experiments in EDFA's in which induced gain gratings provide a mechanism for strong coupling. Such nonlinear wave mixing that uses erbium-doped fiber as a medium can be used to produce dynamic tunable filters, wavelength-division multiplexers, etc. and holds promise for applications in optical communications and other fields.

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