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Nonlinearity in Fiber Transmission

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Abstract—**Procedures are presented for estimating critical powers for nonlinear optical processes in single-mode fiber transmission systems. Crosstalk due to Raman gain in multiplexed systems can appear at powers of a few mW. The effects of self-phase modulation and stimulated Brillouin scattering can appear around 100 mW while typical stimulated Raman threshold powers are a few watts.**

I. Introduction

OPTICAL fibers can exhibit frequency conversion due to nonlinear processes leading to loss, pulse spreading, crosstalk, and in some cases, physical damage. The problems can be particularly severe in very long, low-loss fibers because the central feature of fiber nonlinearities is the exchange of length for optical intensity [1]-[3]. Even so, critical or threshold powers have so far been high enough to justify neglecting optical nonlinearities in transmission system design. Recent interest in single-mode submarine-cable systems may, however, change this situation. Extremely low-loss fibers [4], higher powers [5], and narrow-band lasers all move toward the regime where nonlinear effects become important. Other developments such as small fiber cores to increase the minimum dispersion wavelength [6] and the use of germania glass [7] would also enhance nonlinear effects.

This paper attempts to establish critical powers for various nonlinear processes and to describe their effects in transmission systems. Worst case limits are relatively straightforward to calculate but, as will be seen, these powers can often be safely exceeded. The nonlinear processes of interest are stimulated Raman scattering which serves to illustrate the basic concepts and could lead to crosstalk in wavelength-multiplexed systems, stimulated Brillouin scattering which is the most likely nonlinear loss mechanism, and self-phase modulation which leads to pulse broadening. Another process, parametric four-photon or three-wave mixing, could also cause crosstalk but will only be discussed briefly since these effects would appear at higher powers.

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II. Stimulated Raman Scattering

A. Raman Amplification

The Raman interaction makes a fiber an optically pumped optical amplifier. The process can be viewed as a three-wave parametric amplifier in which pump and signal (called the Stokes wave) are optical waves and the idler is a highly damped vibrational wave. The equivalent quantum mechanical interpretation is one of stimulated scattering by the Stokes photons. Raman amplification depends on the intensity, which is the pump power P divided by the spot size A, the interaction length L, and the Raman gain coefficient g.

$$\text{Amplification} \sim \exp\left|\frac{gPL}{A}\right| . \tag{1}$$

In low-loss fibers the length can be more than a kilometer which, from (1), reduces the power and gain coefficient necessary for significant Stokes amplification.

It is not necessary to inject a signal to see the effects of Raman gain since there is always some light present from spontaneous Raman scattering. If the power and length are large enough, this weak signal can be amplified to the level of pump depletion. Because of the exponential amplification there is only a small difference in pump power between negligible conversion and near total conversion of pump to signal and it is possible to define a threshold or critical power [8].

$$P_c \equiv \frac{16A}{gL} . \tag{2}$$

B. Fiber Parameters

1) Raman Gain Coefficient: The Raman gain coefficient for fused silica as derived from the spontaneous Raman spectrum [9] is shown in Fig. 1. The gain is given for a pump wavelength of 1.0 μm. To convert to a different pump wavelength the gain coefficient scales by $1/\lambda$. At 1.0 μm a shift of 500 cm^{-1} corresponds approximately to 50 nm.

In general, dopants such as boron, germanium, or phos-

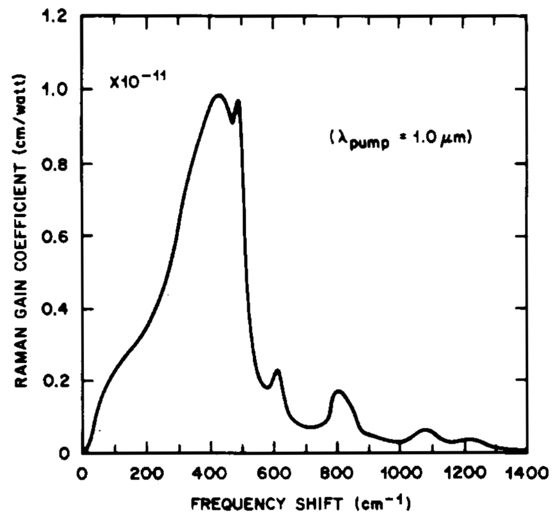

Fig. 1. Raman gain versus frequency shift for fused silica at a pump wavelength of 1.0 μm. The gain coefficient scales inversely with pump wavelength and it is assumed that polarization is maintained.

phorus do not appreciably modify the silica gain spectrum [10], particularly in the small percentages used in extremely low-loss fibers. One should keep in mind, however, that there are glasses such as pure GeO_2 which has a gain coefficient 9.2X that of silica [11]. There are also many silicate glasses with gain curves which look quite different from fused silica [12] although the peak gains are not very different.

2) Length: Amplification will decrease in a long fiber because of pump absorption due to fiber loss. This is handled by replacing L in (1) by an effective length [13]

$$L_{\text{eff}} \equiv \frac{1 - \epsilon^{-\alpha l}}{\alpha} \tag{3}$$

where l is the actual length and α is the linear absorption coefficient. In the present discussion we are usually interested in the limit where $L_{\text{eff}} = 1/\alpha$. For example, $1/\alpha$ in a 1 dB/km fiber is 4.34 km.

3) Power: The power P in (1) is the value at the fiber input but for pulses there is always a question of whether to use peak or average power in the gain calculation. We will use the average power, since in fiber transmission the fibers are long and the optical pulses are closely spaced so group-velocity dispersion will cause relative slippage of pump and Stokes pulses which averages the gain.

4) Area: We will use the fiber core area as the spot size for single and multimode fibers with step or graded boundaries. More careful calculations require computation of overlap integrals [1], [2], [9] but the core-size approximation is adequate within a factor of two. The approximation is very good in single-mode fibers at cutoff of the second mode and for step-index multimode fibers where energy is uniformly distributed through the modes by either the initial excitation or by mode mixing [14]. In single-mode fibers below cutoff the effective area is larger than the core size and in graded index fibers the effective area can be smaller than the core size.

5) Polarization: The Raman gain coefficient in Fig. 1 assumes the ideal case in which the fiber maintains polarization. By maintaining polarization one usually refers to linear polarization but this statement applies to circular and elliptical polarizations as well. In typical single-mode fibers, which do not preserve polarization, the polarizations of pump and stokes waves get out of step and the average Raman gain is reduced by a factor of two [15]. While polarization-maintaining fibers can be made [16], it is likely that such properties would be sacrificed to obtain minimum loss in fiber transmission so we will reduce the Raman gain by a factor of two in all estimates of Raman amplification.

C. Examples of Raman Amplification

Above the stimulated Raman threshold power, light is effectively lost by downshifting to the Stokes Raman frequency. An expression for the threshold power as defined by (2) is given in Table I. Here it is assumed that polarization is not preserved, the spot size can be approximated by the core area, and that the fiber is sufficiently long to replace L_{eff} by $1/\alpha$ in (3). As an example, we choose a single-mode fiber of 8-μm core diameter, 0.3-dB/km loss at a wavelength of 1.5 μm, and a length much greater than $1/\alpha$. The threshold power is then 1.7 W which is probably well above practical power levels for communication applications.

The effects of Raman amplification can appear at much lower powers in wavelength multiplexed systems where energy can be transferred to a longer wavelength channel. We choose as a criterion for a critical power that the amplification of one wavelength by another should be less than 1 percent which corresponds to 20-dB crosstalk. This means that $\exp(gP_cL/A) = 1.01$ so $gP_cL/A = 0.01$ rather than 16 as for the stimulated threshold. In the worst case, one is unlucky enough to choose a frequency separation corresponding to the maximum Raman gain. This case is used for the expression in Table I. For the same example of an 8-μm core fiber at $\lambda = 1.5$ μm the critical power is then 1.1 mW. This shows that it will be essential to keep multiplexed wavelengths separated by more than 500 cm^{-1}.

As a final example, we consider reducing the Raman threshold power with feedback supplied by reflection from poorly matched ends. The condition for oscillation is that the round-trip Stokes amplification equals the combined transmission and reflection loss. Note that backwards Raman gain is the same as forward gain. To simplify the calculation we use the case of a 3 km, 10 μm core fiber at $\lambda = 1.0$ μm and assume the loss at both the pump and Stokes wavelengths is 1.0 dB/km. The fiber length is less than the absorption length so (3) is used to calculate an effective length of 2.17 km. If a reflectivity of 4 percent is arbitrarily chosen for each end, the round trip transmission is 4.0×10^{-4} so gain equals loss at $\exp(2gP_tL/A) = 2500$. Threshold power is now 2.9 W as compared to an 11.8-W single-pass threshold in the same 3-km fiber and a threshold of 5.9 W in a similar fiber of length much greater than $1/\alpha$.

III. Stimulated Brillouin Scattering

Stimulated Brillouin scattering can have a peak gain 300 times that for stimulated Raman scattering so threshold can occur at much lower powers [17]. The interaction is between light and acoustic waves rather than with high frequency optical phonons and because of wave vector matching considerations [1], [3], Brillouin amplification occurs only in the backward direction. The frequency shift is given by

$$\nu_s = \frac{2nV_s}{\lambda} \tag{4}$$

where n is the refractive index and V_s is the velocity of lon-

TABLE I

Threshold and critical powers for stimulated Raman scattering, Raman amplification for wavelength separation corresponding to maximum Raman gain, stimulated Brillouin scattering, and self-phase modulation. Wavelength λ and core diameter d are in μm, fiber loss ξ is in dB/km and laser bandwidth $\Delta\nu$ is in GHz. D is the duty factor. These numbers are calculated in the limit where the fiber is much longer than the absorption length, the approximation that the effective area is the core area, and assuming that polarization is not maintained. As examples, powers are given for an 8 μm core diameter fiber with a loss of 0.3 dB/km at a wavelength of 1.5 μm. For the Brillouin threshold $\Delta\nu$ was 1.0 GHz and the duty factor was 0.5 for the critical power from self-phase modulation.

Stimulated Raman	$P_t = 5.9\times10^{-2} d^2 \lambda \xi$ watts	1.7 W
Raman Amplification	$P_c = 3.7\times10^{-5} d^2 \lambda \xi$ watts	1.1 mW
Stimulated Brillouin	$P_t = 4.4\times10^{-3} d^2 \lambda^2 \xi \Delta\nu$ watts	190 mW
Self-Phase Modulation	$P_c = 2.2\times10^{-3} d^2 \lambda \xi D$ watts	32 mW

gitudinal sound waves. For $\lambda = 1.0\ \mu$m in fused silica, $\nu_s = 17.2$ GHz.

Brillouin gain can be quite different depending on whether the pump linewidth ($\Delta\nu_p$) is much less or much greater than the Brillouin linewidth ($\Delta\nu_B$). Brillouin linewidths are typically around 100 MHz so communications systems will operate in the limit where $\Delta\nu_p \gg \Delta\nu_B$. In this limit the Brillouin gain coefficient for silica-based glasses becomes

$$g = \frac{1.73 \times 10^{-10}}{\lambda^2 \Delta\nu_p} \text{ cm/W} \tag{5}$$

where λ is the wavelength in micrometers, $\Delta\nu_p$ is the pump bandwidth (FWHM) in GHz and the constant contains factors such as the elasto-optic coefficient, the density and the sound velocity. In the opposite limit where $\Delta\nu_p \ll \Delta\nu_B$, $\Delta\nu_p$ in (5) is replaced by $\Delta\nu_B$. As for Raman amplification, the gain is a factor of two higher when polarization is maintained and (5) assumes this ideal situation.

Threshold power for backward stimulated scattering is [8]

$$P_c = \frac{21A}{gL} \tag{6}$$

Equations (5) and (6) are combined to produce the relation for threshold power in Table I. It is assumed in Table I that polarization is not maintained which reduces the gain by a factor of two from the value in (5) [15]. As an example we again choose a 0.3 dB/km, 8.0-μm core diameter fiber, a wavelength of 1.5 μm, and $\Delta\nu_p = 1.0$ GHz. Brillouin threshold power is then 190 mW.

Use of the approximation $\Delta\nu_p \gg \Delta\nu_B$ conceals several complications associated with stimulated Brillouin scattering. For example, the Brillouin linewidth is not a constant but varies [18] as approximately ν_p^2; the value corresponding to $\lambda = 1.0\ \mu$m is 38.4 MHz. Doping modifies $\Delta\nu_B$ in two ways. First is the direct effect on the intrinsic linewidth of the doped glass which has not been well studied. Second is the indirect effect through the change in the sound velocity which from (4) leads to a change in the Brillouin frequency shift between core and cladding because of doping differences [15]. This shows up as an inhomogeneous bandwidth which could be as large as 1 GHz. In weakly doped fibers, however, the effects should be much smaller and need to be included only if the pump linewidth is small enough to be comparable to the Brillouin linewidth.

IV. Self-Phase Modulation

There is an intensity dependent broadening of the signal spectrum from the nonlinear process known as self-phase modulation. This greater frequency width then increases pulse spreading through group-velocity dispersion. The process can be understood as a differential phase shift of the optical carrier between the center and the tails of a pulse due to the intensity dependent refractive index. The index change is extremely small but the corresponding phase modulation can be significant when added up in a long fiber [19]. The effect of the combination of self-phase modulation and group velocity dispersion can be calculated in a straightforward way for simple smooth pulses in single-mode fibers.

The problem of establishing a critical power in a transmission system where the pulses are not simple is less straightforward and we are forced to make some educated guesses.

For simple Gaussian pulses the intensity dependent broadening $\delta\omega$ can be related to the spectral width by

$$\delta\omega = 0.86\, \Delta\omega \Delta\phi_{\max} \tag{7}$$

where $\Delta\phi_{\max}$ is the maximum phase shift in radians and is proportional to the nonlinear index, peak power, effective length and inverse area. Real pulses usually have a frequency width considerably greater than a simple transform of the pulse envelope. This could be due to any combination of phase or amplitude modulation. We will assume that the frequency width is entirely due to amplitude modulation so the pulse contains microstructure on a time scale of $1/\Delta\omega$ where $\Delta\omega$ is the spectral width. For the amplitude modulated pulse the broadening will be proportional to the subpulses so (7) should still apply with $\Delta\omega$ again referring to the spectral width. There is a question about what to use for the peak power. Even if it were known, using the height of the strongest spike would certainly overestimate the broadening. We will use the height of the pulse envelope as given by the average power divided by the duty factor.

To calculate the actual pulse spreading the procedure is to split the fiber into short sections and alternately calculate the effects of self-phase modulation and group velocity dispersion [20]. A simpler approximate approach would be to assume that all the broadening takes place in a length $1/\alpha$ and all the pulse spreading occurs in the remainder of the fiber. Neither of these approaches is amenable to a quick estimate.

A simpler estimate of a critical power [19] can be obtained by assuming that the system has been designed for maximum capacity as set by linear pulse dispersion. A factor of two additional broadening is then a serious problem. This occurs at $\Delta\phi_{\max} = 2.0$ which established a critical peak power of

$$P_c = 1.2 \times 10^{-2} \frac{\lambda A}{L}\ \mathrm{W} \tag{8}$$

where, λ and A are units of μm and $\mu\mathrm{m}^2$, L is in km, linear polarization is preserved, and the constant contains factors such as the nonlinear index. In contrast to Raman gain, the broadening from self-phase modulation is only decreased 17 percent when linear polarization is not maintained in the fiber [19].

The critical power for self-phase modulation as defined in (8) is written in terms of average power in Table I. Here D is the duty factor and polarization is scrambled. The critical power for the 8 μm core, 0.3 dB/km fiber at 1.5 μm is then 32 mW.

We have not treated such details as chirp which could increase or decrease the broadening, or the difference between the positive and negative side of the minimum dispersion wavelength. On the negative side of the minimum dispersion wavelength there should be intensity dependent pulse narrowing [21]. The pulse should first narrow in time and then broaden again. This will decrease the net broadening from group-velocity dispersion. This effect might be used to advantage. For example, at a wavelength of 1.6 μm, in a fiber for which the minimum dispersion is 1.3 μm, the powers required to cause narrowing of 100-ps pulses are on the order of a few milliwatts.

V. Four-Photon Mixing

Four-photon mixing (also called three-wave mixing) is a parametric interaction which can generate new frequencies on either or both sides of the pump frequency [1]-[3]. For example, stimulated Raman or Brillouin light can mix with pump light to produce light on the high frequency side of the pump. These effects require phase matching which can be provided by the differing phase velocities of the waveguide modes in a multimode fiber [22]. In single-mode fibers the process appears only at small frequency shifts ($\sim$1 cm^{-1}) where coherence lengths are of the order of kilometers [23].

It appears at present that this process will not be a serious limit in fiber transmission systems because of the need for phase matching in single-mode fibers and the high powers required in multimode fibers. It should be kept in mind, however, that experiments with high optical powers and multimode fibers almost always produce spectra which combine several nonlinear processes and are made even more complicated by the presence of four-photon mixing.

VI. Conclusion

The foregoing treatment shows that nonlinear effects can appear in single-mode transmission systems at powers of a few milliwatts. The nonlinear processes most likely to cause problems are Raman gain in multiplexed systems, pulse spreading due to self-phase modulation, and stimulated Brillouin scattering with very narrow line sources.

Threshold estimates were based on work done in the visible and it is clear that there is a need for measurements in the spectral range beyond 1 μm—particularly with sources that approximate the spectral and temporal characteristics of real systems.

We have concentrated on the deleterious aspects of fiber nonlinearities but there are also some significant advantages. For example, fiber Raman lasers are a new-type of laser-pumped tunable lasers which utilize both the long interaction lengths of low-loss fibers and the broad Raman bandwidths of glasses [2], [3]. These lasers share many properties with dye and F-center lasers and may someday prove to be compact and inexpensive sources of tunable radiation in the near infrared. Raman lasers in their simple single-pass form have been used to generate a band of optical pulses which have found application in fiber loss and pulse dispersion measurements [24].

There may even be direct system applications of fiber nonlinearities. For example, the nonlinear pulse narrowing in the negative dispersion regime could lead to multiplexed systems where both the minimum dispersion wavelength at 1.3 μm and the low-loss band around 1.6 μm were used at high capacity.

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Fiber Transmission Losses in High-Radiation Fields

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***Abstract*—A summary is provided on the effects of ionizing radiation on present generation optical fibers. In particular, the paper focuses on the magnitude and the spectral and temporal characteristics of the radiation-induced transmission losses in irradiated fibers. The most radiation resistant classes of fibers are identified and possible approaches for further improvements in fiber performance are suggested.**

I. INTRODUCTION

An understanding of the typical radiation effects observed in optical fibers requires some knowledge of the structure and bonding of the optical materials used in waveguide fabrication. Since optical fibers for the most part are manufactured from high-purity glasses based on SiO_2, the discussion of radiation damage will focus on these materials. Ionizing radiation produces broken and dangling bonds which serve as charge trapping sites in the glass matrix [1], [2]. The introduction of index modifying dopants into SiO_2 glass may strongly modify bonding strengths and configurations and can therefore strongly impact on the defect production and charge trapping processes [3]-[5]. In addition, preexisting flaws and strains are common in glasses, so that they are typically much more susceptible to damage from ionizing radiation than their crystalline counterparts of the same composition. Defects in the glasses are normally associated with energy levels within the forbidden gap which result in the formation of lower energy light absorption and emission bands in the near UV, visible and infrared spectral regions. These so called "color centers" are particularly serious in the case of optical fibers since the long optical pathlength can make the optical link vulnerable to rather low radiation doses.

The optical damage which is created within the glass matrix by ionizing radiation is usually not permanent so that recovery and annealing of absorption are observed in most fibers at room temperature. The recovery process is strongly influenced

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