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The Effect of Four-Wave Mixing in Fibers on Optical Frequency-Division Multiplexed Systems

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Abstract—The optical nonlinearity in a single-mode fiber imposes a fundamental limitation on the capacity of optical frequency-division multiplexed (OFDM) systems. In particular, four-wave mixing (FWM) crosstalk may severely degrade the system performance when the fiber input powers are large and/or the channel spacing is too small. Theoretical and experimental results of the effects of FWM in OFDM systems are presented. The theoretical results demonstrate the dependence of FWM on various systems parameters. Also included is an analysis of FWM in both unidirectional and bidirectional transmission systems. The receiver sensitivity degradation from FWM crosstalk was measured in a 16-channel coherent system. A sensitivity penalty of 0.4 dB resulted when a signal power of −3 dBm/channel was transmitted through 12 km of dispersion-shifted fiber.

I. Introduction

The large transmission bandwidth available in optical fibers may be efficiently utilized with optical frequency-division multiplexing (OFDM) using, for example, coherent communication techniques. With compact channel spacing and high optical powers, high-capacity distribution may be realized. With OFDM systems, however, nonlinear interactions in the fiber may pose fundamental limitations on the allowable signal powers and on the spacing of the signal channels [1]–[3]. An example of a nonlinear process is nondegenerate four-wave mixing (FWM). In FWM interactions, three input signals generate a fourth signal which may degrade the system's performance via crosstalk.

In this paper, we describe the limiting effects of four-wave mixing on OFDM systems. In the theoretical section, we describe the FWM dependence on various system parameters such as signal powers, optical channel spacing, and fiber chromatic dispersion. A comparison of FWM in unidirectional and bidirectional transmission systems is also made. In the experimental section, system degradations due to FWM crosstalk in a 16-channel coherent system are described. Based on the experimental results and theoretical calculations, the allowable fiber input powers for different systems configurations are identified.

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II. Theory

When an intense field is applied to a dielectric medium, the bound electrons respond with anharmonic motion [4]. As a result, the induced polarization in the medium is not a simple linear function of the applied field, but becomes a function of higher order products of the field. FWM interaction is an example of such a process which occurs due to third-order nonlinear susceptibility. Although the third-order susceptibility in glass is quite weak, FWM in fibers may be very strong due to large field intensities in the core and the long interaction lengths. In this section, we describe the basic theoretical background for FWM and show how FWM affects various OFDM system configurations.

A. Theoretical Background

Let three signals at frequencies f_i, f_j, and f_k copropagate through a single-mode fiber. Through the nonlinear interaction, a four-wave mixing signal will be generated at a frequency $f_{ijk} = f_i + f_j - f_k$ $(i, j \neq k)$. In our first-order calculation, the FWM power is proportional to the interacting signal powers, and can be expressed as [5], [6]

$$P(f_i + f_j - f_k) = \eta(f_i, f_j, f_k) 1024\pi^6 \chi_{1111}^2 d^2/(n^4\lambda^2c^2) \cdot (L_{eff}/A_{eff})^2 P_i P_j P_k e^{-\alpha L}. \quad (1)$$

Here, λ is the wavelength, c is the vacuum light speed, n is the core index of refraction, L is the fiber length, α is the linear loss coefficient, $P_{i,j,k}$ are launched signal powers, $L_{eff} = \{1 - \exp(-\alpha L)\}/\alpha$ is the effective length, A_{eff} is the effective area of the guided mode [4], d is the degeneracy factor ($d = 3$ for $i = j$, $d = 6$ for $i \neq j$), and χ_{1111} is the third-order nonlinear susceptibility. $\eta(f_i, f_j, f_k)$ is the mixing efficiency given by

$$\eta(f_i, f_j, f_k) = \left(\alpha^2/(\alpha^2 + \Delta\beta^2)\right)\left[1 + 4e^{-\alpha L} \cdot \sin^2(\Delta\beta L/2)/(1 - e^{-\alpha L})^2\right] \quad (2)$$

where $\Delta\beta$ represents the phase mismatch and may be expressed in terms of signal frequency differences

$$\Delta\beta = (2\pi\lambda^2/c)\,|f_i - f_k|\,|f_j - f_k| \cdot \left\{D + dD/d\lambda(\lambda^2/2c)\left(|f_i - f_k| + |f_j - f_k|\right)\right\}. \quad (3)$$

Here, D is the fiber chromatic dispersion. The efficiency decreases with increasing signal frequency difference, chromatic dispersion, or transmission length due to increased phase mismatch between the signals [6], [7]. Fig. 1 shows a plot of the mixing efficiency as a function of input signal frequency differences for two values of fiber chromatic dispersion. The assumed length of the fiber is 12 km. With large chromatic dispersion, for example, experienced by a 1.5-μm signal propagating through a conventional single-mode fiber, the mixing efficiency drops for signals whose frequencies are different by more than a few tens of gigahertz. On the other hand, when the chromatic dispersion is small (e.g., 0.3 ps/nm·km), the efficiency remains strong up to nearly 100 GHz. Therefore, the effect of FWM may be significantly stronger when conventional fibers are used with 1.3-μm sources or when dispersion-shifted fibers are used with 1.5-μm sources.

B. FWM in OFDM Systems

In many OFDM systems, spacing between the signal channels may be uniform in the range of a few gigahertz to about 10 GHz. In such systems, at any particular channel frequency, there will be a number of FWM waves generated from various combinations of interacting signals. Assuming that the signals experience negligible nonlinear loss in fiber, the total FWM power generated at frequency f_m may be expressed as a summation:

$$P_{tot}(f_m) = \sum_{f_k = f_i + f_j - f_m} \sum_{f_j} \sum_{f_i} P(f_i + f_j - f_k). \quad (4)$$

The different FWM contributions in this summation may be simplified and identified by the use of a table. Table I shows an example for a uniformly spaced 16-channel system, and identifies frequencies which mix to produce FWM waves at the position of the eighth frequency. The columns and rows correspond to index "i"'s and "j"'s in (4), respectively. The entries in the table correspond to the index "k." For example, laser 4 ($i = 4$) and laser 15 ($j = 15$) interact with laser 11 ($k = 11$) to produce an FWM signal at the position of laser 8 ($m = 8$). The contributions where $i = k$ or $j = k$ are neglected; they correspond to cases of self- and cross-phase modulation, not to FWM signal generation. Because the degeneracy factor is already accounted for in (1), the indexes i and j are interchangeable, and one needs only to consider half-space in the table. The degeneracy factors are $d = 3$ and 6 for the diagonal and off-diagonal elements, respectively.

The number of waves generated grows rapidly with the increasing number of channels. For example, in a four-channel system, there are five FWM waves generated at the second- and third-channel frequencies. At the center channel frequencies of a 16-channel system, there are 84 wave contributions. However, the strength of each wave is weighted according to the mixing efficiency $\eta(f_i, f_j, f_k)$; hence, the total FWM power depends critically on the extent of phase mismatch between the signals.

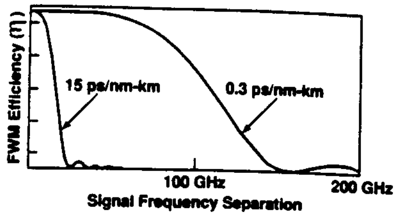

Fig. 1. FWM efficiency (linear scale) versus effective signal frequency difference. The effective signal frequency difference is defined as $(|f_i - f_k||f_j - f_k|)^{1/2}$. Fiber length: $L = 12$ km; linear loss: $\alpha = 0.2$ dB/km; $dD/d\lambda = 0.09$ ps/km · nm^2.

TABLE I
FWM CONTRIBUTIONS AT THE FREQUENCY OF CHANNEL 8 IN A 16-CHANNEL OFDM SYSTEM

(The input signals at frequencies f_i, f_j, and f_k interact such that $f_8 = f_i + f_j - f_k$. In a unidirectional OFDM system, no FWM waves are generated from combinations of frequencies where $i = k$ or $j = k$.)

j = \ i =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1									2	3	4	5	6	7	8	9
2				k =			1		3	4	5	6	7	8	9	10
3						1	2		4	5	6	7	8	9	10	11
4					1	2	3		5	6	7	8	9	10	11	12
5					2	3	4		6	7	8	9	10	11	12	13
6						4	5		7	8	9	10	11	12	13	14
7							6		8	9	10	11	12	13	14	15
8																
9									10	11	12	13	14	15	16	
10										12	13	14	15	16		
11											14	15	16			
12												16				
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The fiber length dependence of the FWM interference is shown in Fig. 2. The plot assumes a 16-channel, 10-GHz-spaced system. The vertical axis shows the relative FWM power, which is a ratio of the FWM power at f_8 to the fiber output signal power [1]. Since the two powers experience the same linear loss, the exponential attenuation is factored out in this plot. The initial rise in crosstalk is due to the increase in nonlinear interaction length. With longer lengths, the crosstalk becomes constant due to large phase mismatch. When the fiber chromatic dispersion is large, phase mismatch occurs quickly with shorter fiber lengths; hence, the relative FWM power remains constant throughout the span.

C. Bidirectional Transmission Systems

In the preceding discussions, we have assumed that all the signals are copropagating in the fiber. Counterpropagating signals may also interact to generate FWM waves as long as the phase-matching condition is roughly satisfied. Fig. 3 shows an example of FWM in a counterpropagating geometry. Two counterpropagating signals at f_1 and a forward propagating signal at f_2 generate backward propagating waves at f_0 and f_2 and forward propagating waves at f_0 and f_3. The expression for FWM power given

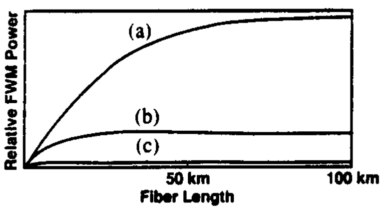

Fig. 2. Relative FWM power defined as $P_{FWM,tot}(f_8)/(P_s e^{-\alpha L})$ versus fiber transmission length where P_s is the launched signal power per channel, assumed to be equal for all channels. A 16-channel system with 10-GHz channel spacing is assumed. (*a*) $D = 0.3$ ps/nm · km, (*b*) $D = 1$ ps/nm · km, (*c*) $D = 15$ ps/nm · km.

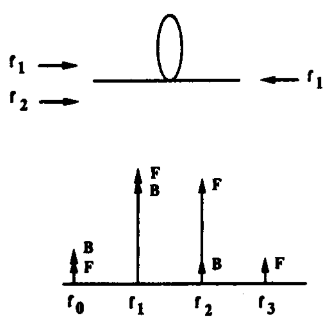

Fig. 3. Copropagating and counterpropagating FWM. The frequencies of launched signals and FWM waves are indicated. *F*: forward propagating. *B*: backward propagating.

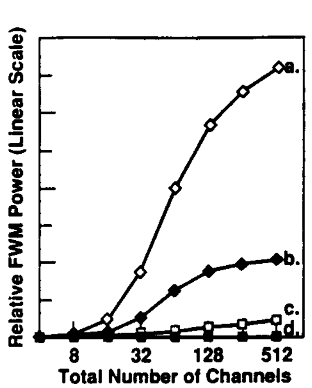

Fig. 4. Total FWM power at center channel frequency versus toal number of channels for unidirectional and bidirectional OFDM systems. Channel spacing = 10 GHz; $L = 12$ km; $\alpha = 0.2$ dB/km; $dD/d\lambda = 0.09$ ps/km · nm². (*a*) Bidirectional, $D = 0.3$ ps/nm · km. (*b*) Unidirectional, $D = 0.3$ ps/nm · km. (*c*) Bidirectional, $D = 15$ ps/nm · km. (*d*) Unidirectional, $D = 15$ ps/nm · km.

by (1) is correct for a particular set of mixing signals; however, the summation and the degeneracy factor must be reconsidered to calculate the total FWM power in bidirectional OFDM systems. As in the case for unidirectional systems, we assume that the generated FWM waves are incoherent with respect to one another and take the summation of FWM powers.

Let us assume that the channel spacing is uniform, and that identical channel frequencies are used for signals propagating in both directions. In any one direction, when the input signal frequencies are nondegenerate (i.e., $f_i \neq f_j \neq f_k$), twice as many waves are generated at a particular frequency due to interactions between counterpropagating signals compared to copropagating signals. Hence, the total contribution from mixing between nondegenerate frequencies is three times greater in a bidirectional system. When two of the frequencies are the same, i.e., $f_i = f_j \neq f_k$, $f_i = f_k \neq f_j$ or $f_i \neq f_k = f_j$, there are additional contributions with a new degeneracy factor of $d = 6$ compared to $d = 3$ in the unidirectional case since the signals at the same frequency are now spatially nondegenerate. In particular, when the signal frequencies f_i or f_j and f_k are equal and are counterpropagating, FWM signals can result with automatic phase matching, even when the frequency difference is very large. It must be remembered that when these signals are copropagating (with $f_i = f_k \neq f_j$ or $f_i \neq f_k = f_j$), the result is cross-phase modulation and not FWM signal generation. Fig. 4 shows the FWM power generated at a center channel for unidirectional and bidirectional systems. Due to the counterpropagating FWM contributions with automatic phase matching, the total FWM power increases, even when channel numbers are large with only a very small "saturation" effect. Hence, in bidirectional systems, the input powers and/or the channel spacings must be relaxed, especially when the total number of channels is large.

III. Experiment

In our initial set of experiments, we generated FWM signals by copropagating two laser outputs through a fiber, as shown in Fig. 5. We used 1.5-μm lasers and a 12-km span of dispersion-shifted fiber with chromatic dispersion of −0.3 ps/nm·km at the signal wavelength. FWM signals were detected via the heterodyne technique using a third laser which acted as an LO. Input signal polarizations were adjusted to maximize the FWM signal. Fig. 6 shows the frequencies and the powers of input and FWM signals. With input powers of 0 dBm, FWM signals with −46-dBm power were generated with nearly unity mixing efficiency.

Coherent receiver sensitivity degradation has recently been measured using an FWM signal generated in the manner described above [2]. However, the crosstalk effects due to a single coherent FWM wave are quite different from the effects of multiple waves generated by many combinations of signal channels. It is also important to use modulated signal lasers so that the FWM waves have realistic spectra. We have conducted an experiment using a 16-channel coherent system and studied the crosstalk from multiple FWM waves [8], [9].

A. Multichannel FWM: Experimental Arrangement

The setup used in our 16-optical-channel experiment is shown in Fig. 7. The signal sources were DFB laser modules at wavelengths around 1.54 μm, with a total wavelength span of less than 2 nm. One of the lasers, laser 7, was optically FSK-modulated with a 155-Mb/s pseudorandom data stream in the FSK-alternate-mark-inversion (AMI) signal format. A frequency deviation of ±1.8 GHz was used. The other 15 lasers were modulated with in-

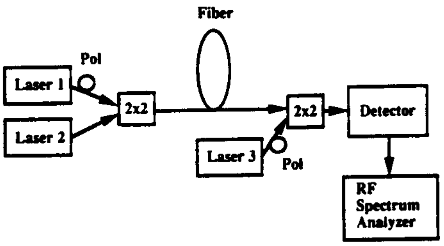

Fig. 5. Experimental configuration for FWM signal generation using two input signals. Pol: polarization controller.

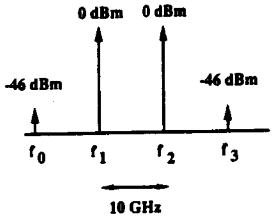

Fig. 6. FWM signal frequencies and power levels.

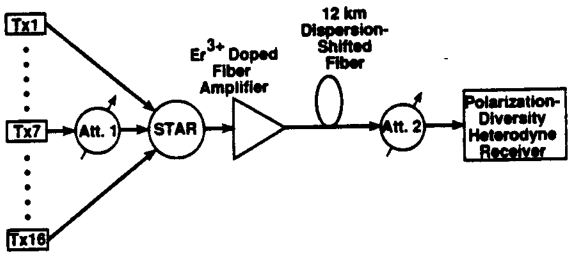

Fig. 7. Experimental arrangement for a multichannel coherent system.

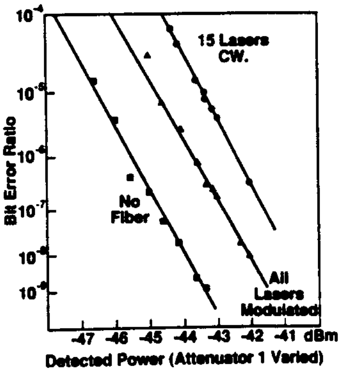

Fig. 8. Bit-error ratio (BER) measurement on laser 7. Attenuator 1 was varied to make this measurement. (Squares: no fiber; triangles: all lasers modulated; circles: 15 lasers CW.)

dependent FSK-AMI data streams derived from digital video coders. The channel spacing was set at 10 GHz, and the relative frequencies between all the lasers were stable to within ±50 MHz, as observed on the RF spectrum analyzer. The lasers were not actively frequency-stabilized during the experiment, and the observed stability was due to the thermal stability of packaged LD's.

The 16 outputs were combined using a 16 × 16 star coupler. The output of the star coupler was amplified with an alumino-silicate erbium-doped fiber amplifier [10]. The 16 laser wavelengths fell within the flat gain region of the amplifier and experienced 11-dB gain. The amplified signals at −3 dBm/channel were launched into the 12-km span of the dispersion-shifted fiber. The output of the fiber was transmitted to a polarization diversity heterodyne receiver where the bit-error ratio (BER) of laser 7 was studied. Although the center channels for a 16-channel system correspond to channels 8 and 9, the difference in FWM noise contributions at the center channels and channel 7 is negligible. The receiver consisted of a single 1.5-GHz bandpass filter centered about an IF of 2.25 GHz, and detected the "0"'s of the AMI signal [11].

B. Results

Fig. 8 shows the BER as a function of the detected power of laser 7 with (triangles and circles) and without (squares) the fiber. When the transmission fiber was removed, the system was limited by the receiver thermal noise. The BER was measured by varying attenuator 1, which changed the power of laser 7 without affecting the other 15 lasers. A sensitivity degradation of 3.0 dB was measured when only laser 7 was modulated and the other lasers were operated in the CW mode. When all 16 lasers were modulated, the sensitivity penalty was smaller at 1.8 dB. The reason for the smaller penalty is that the FWM spectrum spreads when the interacting signals are modulated. As a result, the receiver IF filter captures less interfering noise and the crosstalk is reduced.

At the detected power of −42 dBm, the power of laser 7 was 8 dB below the average power of the other lasers. In our experiment, the received power for laser 7 could not be directly measured due to the presence of the other 15 lasers. Instead, the received signal power was calculated from our measurements of laser 7 power and the total combined power after the star coupler. Our calculation was based on the assumption that the ratio of laser 7 power to the total power stayed constant in the amplifier and the fiber. We believe that this assumption was valid since the gain in the fiber amplifier remained independent of changes in laser 7 power.

The spectral characteristic of the FWM noise was studied by frequency-tuning laser 7 relative to its allocated channel frequency. The LO was also tuned to maintain a constant IF frequency. Fig. 9(a) depicts negative detuning of laser 7. Due to the large frequency deviation used to modulate the lasers, the spectral width of each signal laser was over 5 GHz (not shown in the figure). With negative detuning of laser 7, laser 6 image interference is expected [12]. Fig. 9(b) depicts positive detuning of laser 7. With both laser 7 and LO frequencies tuned higher than the channel 7 frequency, the FWM image band is expected to cause crosstalk. With greater positive detuning, direct crosstalk from laser 8 is expected to dominate the FWM noise.

Fig. 10 shows the BER as a function of frequency detuning. When 15 lasers ran CW, the FWM interference was pronounced at $\Delta f = 0$, at the allocated position of channel 7 (curve (a)). When all the lasers were modu-

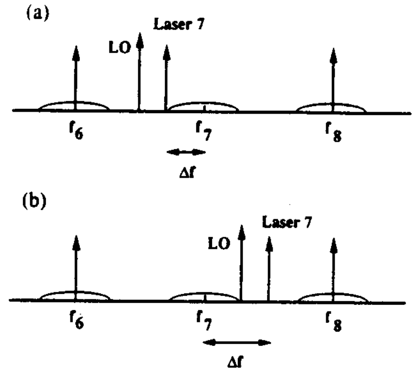

Fig. 9. Frequency detuning of laser 7 to measure the spectral spread in the FWM noise. The figure also shows the broad spectra of interfering FWM waves which are generated when all the lasers are modulated. (a) When laser 7 is negatively detuned, channel 6 image-band interference occurs. (b) When laser 7 is positively detuned, the FWM image interference occurs. With detuning >6 GHz, channel 8 crosstalk occurs.

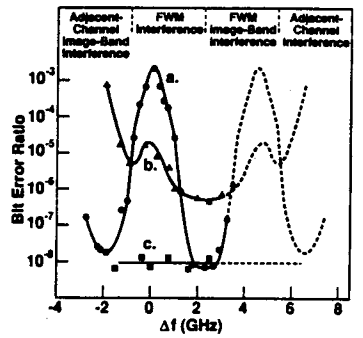

Fig. 10. BER as function of laser 7 detuning. The dashed curve shows the frequency regime where the FWM crosstalk occurs via image-band interference. (*a*) 15 Lasers CW. (*b*) All lasers modulated. (*c*) No fiber.

lated, the BER degradations were less severe at $\Delta f = 0$, but crosstalk occurred over a wider frequency range (curve (*b*)). The increase in the BER below $\Delta f = 2$ GHz was due to laser 6 image interference, corresponding to the case illustrated in Fig. 9(a). The dashed curve shows an increase in the BER above $\Delta f = +2$ GHz due to the FWM image interference illustrated in Fig. 9(b). The expected increase in the BER above $\Delta f = +6$ GHz is from laser 8 crosstalk. Curve (*c*) shows the measurement taken without the fiber. The BER was constant in the range between $\Delta f = -2$ GHz and $\Delta f = 2$ GHz, as expected.

It has been previously suggested that the use of nonuniform channel spacing may alleviate the problem of FWM crosstalk [13]. However, when all the lasers were modulated, FWM interference was measured at all frequencies between the adjacent channels. This result indicates that the spectral spread of the FWM noise is an important consideration when allocating nonuniform channel spacing, especially in heterodyne systems where the FWM image also causes crosstalk.

C. Discussion

Our theoretical discussion described FWM between signals in identical polarization states. While mixing also occurs between x-polarized and y-polarized signals, the resulting FWM power is weaker by a factor of 9. In our experiment, no attempt was made to control polarization in the fiber, and the signals were observed to be randomly polarized with respect to one another. The resulting FWM waves were in a similar random state of polarization, and the polarization diversity receiver captured both the x- and y-polarized components. The experiment represents a realistic system without polarization control and did not represent the worst case situation. A greater sensitivity penalty will result if the polarization states of the signals are accidentally or intentionally aligned.

In the experiment described, the dominant noise source was the receiver thermal noise. The amplified spontaneous emission noise from the fiber amplifier was attenuated by nearly 30 dB before reaching the receiver, and we verified that this noise contribution was negligible. From the measured FWM penalty of 1.8 dB, we conclude that the electrical noise power due to FWM crosstalk was approximately half the receiver noise without FWM.

Based on the initial experiment with two input signals (see Figs. 5 and 6), an estimate of the FWM optical power in the 16-channel experiment was made. Assuming that the signal beams were polarized randomly with respect to one another, the sum of FWM power generated at f_7 was calculated to be -36 dBm at the fiber output. This power was approximately 20 dB below the laser 7 signal power at the fiber output. Because the exact polarization states of the signals were unknown, there is an inherent uncertainty associated with our estimate of the total FWM power. If the signal polarizations were exactly aligned, the estimate of FWM power would be -31 dBm. The generated FWM power was attenuated by about 25 dB between the fiber and the receiver. At the receiver, only a fraction of the detected FWM power was converted to electrical noise since the modulated FWM spectrum was wider than the IF filter bandwidth.

As described earlier, we found it convenient to attenuate the power of laser 7 independently during the BER measurement. However, in practical systems, the signal powers of all channels are expected to be uniform. Any attenuation following the fiber is experienced both by the signal and the FWM noise. If the signal powers for all 16 lasers were kept constant and the attenuator following the fiber was adjusted to measure the BER, the penalty at 10^{-9} error ratio would be 0.4 dB. This penalty was calculated based on the assumption of fixed signal-to-noise ratio for fixed BER, and on the assumption that the electrical noise power due to FWM was proportional to attenuation after the fiber.

Fig. 11 shows a plot of the maximum allowable input signal power per channel versus the total number of channels for various channel spacings and chromatic dispersions. We have used a criterion corresponding to our experimental result of 0.4-dB penalty. The point corresponding to our 16-channel experiment is indicated. We have fitted the theoretical trends to our experimental data

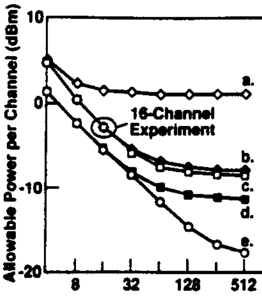

Fig. 11. Maximum allowable power per channel versus total number of channels. $L = 12$ km, α 0.2 dB/km, $dD/d\lambda = 0.09$ ps/nm^2 · km. (*a*) Unidirectional system, $D = 15$ ps/nm · km, channel spacing = 10 GHz. (*b*) Unidirectional system, $D = 15$ ps/nm · km, channel spacing = 2 GHz. (*c*) Unidirectional system, $D = 0.3$ ps/nm · km, channel spacing = 10 GHz. (*d*) Bidirectional system, $D = 0.3$ ps/nm · km, channel spacing = 10 GHz. (*e*) Bidirectional system, $D = 0.3$ ps/nm · km, channel spacing = 2 GHz.

point, having also assumed that the input signals are polarized randomly with respect to one another. When the total number of channels is increased, the allowable input power decreases. However, because the number of channels which can interact strongly is limited by the phase mismatch in the fiber, the allowable input power becomes constant when the total number of channels becomes very large. The power tolerance is the greatest for unidirectional systems using relaxed channel spacings and fibers with large chromatic dispersion. For example, the maximum allowable power is about 0 dBm/channel in a 10-GHz-spaced, 100-channel system using a conventional fiber and 1.5-μm sources. The power restriction is most severe for bidirectional systems using narrow channel spacing and low dispersion fiber. In such systems, FWM crosstalk may become a severe problem, even with input powers of less than −10 dBm/channel.

Despite the large number of channels used in other recent OFDM system experiments, FWM crosstalk did not pose a problem because the power per channel was generally low in the range of −10 to −20 dBm, and because the conventional nondispersion-shifted fibers were used [12], [14]. However, single-mode lasers with output powers greater than 20 dBm are currently available [15]. Optical amplifiers with saturation powers exceeding 20 dBm have also been recently reported [16]. With the development of such technologies, power levels in the range of −10 to 0 dBm/channel are possible, even after the star coupler splitting loss. In designing future OFDM systems, signal powers and the channel spacing must be carefully specified, taking into account the dispersion in the fiber used. Of equal importance are the relative locations of the star coupler, the amplifiers, and the transmission fiber; these components must be located such as to balance the effects of splitting loss, fiber FWM noise, and the amplifier noise. With these careful considerations, one can successfully design a high-capacity OFDM system with large broadcasting capability.

IV. Conclusion

We have carried out experimental and theoretical studies of four-wave mixing in transmission fiber in OFDM systems. We have shown that a sensitivity degradation of 0.4 dB results when a signal power of −3 dBm/channel is launched into a 12-km span of dispersion-shifted fiber in a 16-channel coherent system operated in the 1.5-μm wavelength region. The spectral extent of the FWM noise was also measured by detuning the signal frequency relative to its allocated channel frequency. When all the lasers were modulated, crosstalk was observed at all frequencies between the two adjacent channels.

Our theoretical studies indicate that FWM leads to significant system degradations when channels are closely spaced, signal powers are high, and chromatic dispersion is low. For example, FWM crosstalk becomes significant when the signal powers exceed 0 dBm/channel in a 10-GHz-spaced, 100-channel system using 1.5-μm sources and a conventional fiber. For the same system, the allowable signal power is −8 dBm/channel when a dispersion-shifted fiber is used. Thus, successful design of high-capacity OFDM systems must include careful consideration of possible FWM interactions in the transmission fiber.

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