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Wavelength Encoding to Reduce Four-Wave Mixing Crosstalk in Multi-Wavelength Channels

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The trend toward higher bit rates in lightwave communications has increased interest in dispersion-shifted fiber (DSF) to minimize dispersion penalties. In addition, wavelength-division multiplexing (WDM) is being used to gain even greater capacity, and broad bandwidth erbium-doped fiber amplifiers are extending link distances between signal regeneration. Taken together, these techniques can result in severe performance degradation due to four-wave mixing (FWM) [1, 2, 3]. Several different ways of reducing the FWM degradation in WDM systems have been proposed, but all of the approaches increase system complexity and make it difficult to add channels to the system.

We show that wavelength-coded multiplexing can provide multiple channels on a simple fiber link while significantly reducing four-wave mixing interference compared to a WDM system. The FWM spectrum is symmetric and use of an antisymmetric code cancels the interference. Wavelength-coded multiplexing, also known as spectral code-division multiplexing (SCDM), has been proposed and demonstrated in optical fiber local area networks [4, 5, 6].

In a SCDM system each channel is assigned a combination of wavelengths (chips) as the channel's code, and the modulated signals of all channels are combined, propagate along the long-haul dispersion-shifted fiber, and experience attenuation and spectrum deformation due to FWM. Each receiver performs spectral correlation decoding with the same code as that of the corresponding transmitter, to pick out the desired signal and reject the signals from the other channels.

The key to good performance in a SCDM system is the orthogonality of the codes: the codes must have high autocorrelation and low crosscorrelation. A scheme for implementing truly orthogonal bipolar codes, as used in rf systems, in a noncoherent optical system has been proposed and experimentally demonstrated [4, 5]. To realize bipolar encoding/decoding in a unipolar system, a user k needs to send two sequences of unipolar codes $\mathbf{U}_k$ and $\overline{\mathbf{U}_k}$. $\mathbf{U}_k$ is obtained by replacing each -1 in the bipolar code with 0; $\overline{\mathbf{U}_k}$ is the complement of $\mathbf{U}_k$. The bipolar codes can be any orthogonal codes, say Walsh codes of length N. One way of sending the two distinct sequences is to concatenate them into one longer code, a form of wavelength multiplexing. There are many ways of concatenating $\mathbf{U}_k$ and $\overline{\mathbf{U}_k}$. The scheme we examine here is

$$\begin{aligned}\mathbf{U}_k \oplus \overline{\mathbf{U}_k} \;=\; & \Big[U_k(1), U_k(2), \cdots, U_k(N), \\ & \overline{U_k(N)}, \overline{U_k(N-1)}, \cdots, \overline{U_k(1)}\Big], \quad (1)\end{aligned}$$

where $\oplus$ represents concatenation. We denote the concatenated code for user k by $\mathbf{V}_k = [V_k(1), V_k(2), \cdots, V_k(2N)]$. This code can be called "antisymmetric" in the sense that it satisfies the relation: $V_k(i) = \overline{V_k(2N+1-i)}$, $i = 1, 2, \cdots, 2N$.

In the spectral domain, the encoding and decoding are implemented by dispersing the optical signal and filtering it with an amplitude mask in the wavelength plane. The pattern of the mask corresponds to the code. The transmitter for channel k encodes the signal according to the symbol source: $\mathbf{V}_k$ for bit "1" and $\overline{\mathbf{V}_k}$ for bit "0"; both $\mathbf{V}_k$ and $\overline{\mathbf{V}_k}$ are antisymmetric codes.

In channel k's receiver, the signal is split and correlated with the two complementary codes $\mathbf{V}_k$ and $\overline{\mathbf{V}_k}$. The decision statistic for channel k is given by the difference of the correlation signals detected by two photodiodes. This technique allows unipolar systems to implement the orthogonality of bipolar codes to reject signals from the other channels.

The FWM process destroys the orthogonality of the correlation detection and leads to crosstalk, i.e., the bits sent in other channels affect the decision statistic of channel k. In order to evaluate the performance of the SCDM system, we calculate the variation of the decision statistic caused by FWM in the fiber. The power spectrum at the input of the fiber, which is the sum of the power spectrum of the N users, is a random variable vector. The power in each chip is a random variable with a probability distribution that approaches Gaussian for a large number of users. The

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power of the optical signal generated by FWM in chip i is given by

$$P_F(i) = C \sum_{i=i_1+i_2-i_3} P(i_1)P(i_2)P(i_3), \qquad (2)$$

where the $P(i)$, are the fiber input power in three chips, and the factor C contains the fiber attenuation, length, and nonlinearity. For operation near the zero-dispersion frequency, the total phase matched bandwidth is several terahertz and it is reasonable to assume that all FWM combinations are phase matched.

Since the $P(i)$ are random variables, $P_F(i)$ is also a random variable, with mean value proportional to $N_F(i)$, the number of possible FWM combinations for chip i. $N_F(i)$ is obtained by counting the number of different sets of (i_1, i_2, i_3) that satisfy $i_1 + i_2 - i_3 = i$ with the restriction that $1 \leq i_1, i_2, i_3 \leq 2N$ and $i_1 \neq i_3, i_2 \neq i_3$; the result is

$$N_F(i) = (N-1)(3N-1) - (N-i)(N-i+1), \quad (3)$$

where $i = 1, 2, \cdots, 2N$. The number of FWM combinations per chip, and thus the FWM spectrum, is symmetric by nature, i.e., $N_F(i) = N_F(2N+1-i)$, for $i = 1, 2, \cdots, 2N$. The contribution of FWM to the decision statistic is given by $Z_k = \mathcal{R}\mathbf{P}_F \cdot \mathbf{V}_k - \mathcal{R}\mathbf{P}_F \cdot \overline{\mathbf{V}}_k$, where $\mathcal{R}$ is the detector responsivity. The mean value of Z_k is proportional to a sum of terms of form $N_F(i)[V_k(i) - \overline{V_k}(i)]$. Since $N_F(i)$ is symmetric and $V_k(i)$ and $\overline{V_k(i)}$ are antisymmetric for every channel k, $\langle Z_k \rangle = 0$.

While the mean value of the decision statistic is zero, this does not mean there is zero interference. We must look at second order effects, the variance of Z_k. It is easy to show that the standard deviation of FWM crosstalk is linear in the number of channels N in a SCDM system. In contrast, the mean value of FWM crosstalk in a WDM system does not cancel and is proportional to N^2.

We have calculated the error probability in the SCDM system considering only shot noise, thermal noise and FWM crosstalk, all of which are assumed to have a Gaussian distribution. For comparison, we also derived an expression for the error probability in a WDM system. The fiber and system parameters used in the calculations are listed in Table 1.

In Fig. 1 the error probability of a SCDM system is compared to that for a WDM system as a function of the signal power. For all power levels the SCDM system performance exceeds that of the WDM system. The cancelation of the mean value of FWM crosstalk in the SCDM system implies that for the same performance level, longer fiber links between regeneration can be used as compared to a WDM system, resulting in significant economic benefits. The SCDM coding will also cancel any other wavelength-symmetric noise sources, providing additional improvements. We are currently planning experimental verification of the predicted performance improvements.

Table 1: The fiber and system parameters used in the calculation of the error probability.

Number of channels	N	100
Fiber length	L	100 km
Fiber attenuation	α	0.25 dB/km
Fiber nonlinearity	κ	$5.84 \times 10^{-6} \mathrm{m}^{-2}\mathrm{W}^{-2}$
Wavelength	λ	1.55 μm

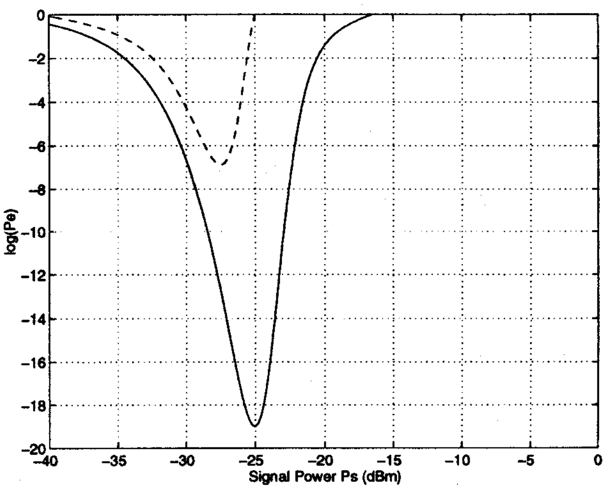

Figure 1: Error probability as a function of signal power for the SCDM system (solid curve) and WDM system (dashed curve) under the influence of four-wave mixing for the parameters of Table I.

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