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Wavelength Shift Keying Technique to Reduce Four-Wave Mixing Crosstalk in WDM

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Abstract ---In low dispersion fibers, FWM spectrum is symmetric around the zero dispersion point. Wavelength shift keying technique using symmetric wavelengths and balanced detection can cancel FWM crosstalk to first order.

Wavelength division multiplexing (WDM), zero or low dispersion fibers, and Er-doped fiber amplifiers are being used in long-haul communications links to increase capacity and to extend distances between signal regeneration. Taken together, these techniques can result in severe performance degradation due to four-wave mixing (FWM) [1,2]. Several methods have been proposed to reduce the effects of FWM crosstalk [3,4], but generally these increase the difficulty of adding channels to the system. We describe a WDM wavelength shift keying technique that completely cancels FWM interference to first order. Modeling shows that this technique substantially improves performance relative to standard on-off WDM encoding; experimental testing of the technique is underway.

Four-wave mixing is a third-order nonlinear process in optical fibers in which two or more wavelengths combine and produce several mixing products. For uniformly spaced WDM channels, the generated FWM waves fall onto other active channels in the band, causing interchannel crosstalk. For operation near the zero dispersion wavelength, all FWM combinations are easily phase matched, causing significant interference and thereby hampering system performance. Therefore, Four-wave mixing becomes the main concern for WDM using low dispersion fibers, i.e. dispersion shifted fibers.

Calculations show that the FWM spectrum is symmetric around the zero dispersion point [5] and therefore can be significantly depressed using symmetric wavelength assignment and balanced detection. In WDM wavelength shifted keying, each user is assigned two specific wavelengths that are symmetric with respect to the zero dispersion wavelength. One wavelength is used to transmit symbol "*1*", while the other is used to transmit symbol "*0*". The modulated signals of all users are combined, propagate along the long-haul dispersion-shifted fiber, and experience attenuation and spectrum deformation due to FWM. At the receiver, narrow band filters select the desired user's two wavelengths and they are detected by a balanced receiver. The received signal is positive for symbol "*1*"and negative for symbol "*0*".

While wavelength shift keying requires twice as many wavelengths to support a given number of data channels, it has a number of advantages. Complementary keying has a 3 dB signal to noise advantage over on-off keying; dispersion shifted fiber permits higher transmission rates; and detection of both data symbols involves detection of energy at a non-zero threshold, reducing sensitivity to noise of all types. The balanced detection cancels all noise having a uniform spectral distribution and symmetric assignment of symbol wavelengths around the zero dispersion wavelength cancels FWM interference to first order.

Our model assumes N users in the system, each transmitting the same power P_0 for every data bit. The power of the optical signal generated by FWM in wavelength *i* is given by

$$P_F(i) = C \sum_{i=i_1+i_2+i_3} P(i_1)P(i_2)P(i_3) \qquad (1)$$

Where the *P(i)* are the fiber input power in three wavelengths, and the factor *C* contains the fiber attenuation, fiber length, nonlinearity and phase-matching efficiency [7].

The mean value of $P_F(i)$ is proportional to $N_F(i)$, the number of possible FWM combinations for wavelength *i*. $N_F(i)$ is obtained by counting the number of different sets of (i_1, i_2, i_3) that satisfy $i_1 + i_2 = i$ with the restriction that $1 \le i_1, i_2, i_3 \le 2N$ and $i_1 \neq i_2$, $i_2 \neq$, i_3; the result is

$$N_F(i) = (N-1)(3N-1) - (N-i)(N-i+1) \quad (2)$$

where $i = 1,2,\ldots,2N$; The number of FWM combinations for each wavelength, and thus the FWM spectrum, is symmetric by nature, i.e. $N_F(i) = N_F(2N+1-i)$, for $i = 1,2,\ldots,2N$. Since the balanced receiver of each user subtracts the powers of two symmetric wavelengths, the mean of FWM generated power is canceled.

In a wavelength shift keying system, the decision statistic complies to that of a antipodal system, $Z_k = 2RPs$ for bit "*1*"and $Z_k = -2RPs$ for bit "*0*", where *Ps* is the received signal power in one wavelength, and *R* is the detector responsivity. The FWM contribution to the decision statistic has zero mean. The standard deviation of FWM crosstalk, however, is linear in the number of users. In contrast, the standard WDM system has a decision statistic of an orthogonal system, $Z_k = RPs$ for bit "*1*"and $Z_k = 0$ for bit "*0*". FWM crosstalk does not cancel and is proportional to the square of the number of users.

We have calculated the error probability in the wavelength shift keying system considering only shot noise, thermal noise and FWM crosstalk, all of which are assumed to have a Gaussian distribution. For comparison, the error probability of a standard WDM system is also derived. The fiber and system parameters used in the calculations are listed in Table 1. The parameters were chosen for a comparison of WDM performance with measurements of 8 users [3].

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

Number of channels	N	*8*
Fiber length	L	*137Km*
Fiber attenuation	α	*0.24dB/Km*
Fiber dispersion	$dD/d\lambda$	$0,055 ps/Km\text{-}nm^2$
Fiber nonlinearity	κ	$5.84´10^{-6}m^{-2}W^{-2}$
Wavelength	λ	*1.55mm*

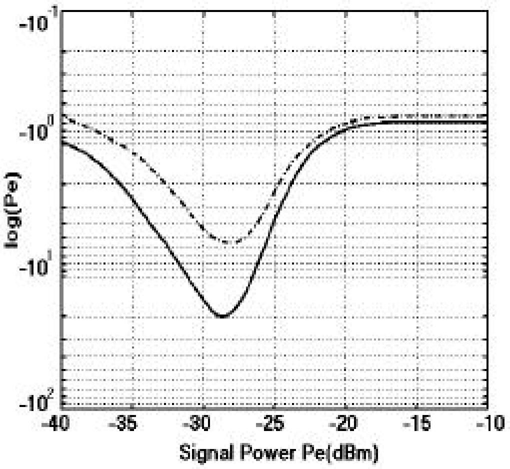

Figure 1: Error probability as a function of signal power for the wavelength shift keying WDM system (solid curve) and standard WDM system (dashed curve) under the influence of four-wave mixing for the parameters of Table 1.

In Fig. 1 the error probability of wavelength shift keying is compared to that of a standard WDM system in the case of 8 users as a function of the signal power. The WDM calculation matches reference data very well [3]. For all power levels the wavelength shift keying system performance exceeds that of the standard system. The BER of the standard WDM is larger than 10^{-6} while for the wavelength shift keying system, there is a signal power range within which the BER is lower than 10^{-10}. Wavelength shift keying will also cancel any other wavelength-symmetric noise source, providing additional improvements. Experiments are underway to verify the wavelength shift keying calculations.

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