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ON/OFF RATIO DEGRADATION OF HIGH DENSITY WDM SYSTEMS DUE TO RAMAN CROSSTALK

Indexing terms: Optical Communications

The ON/OFF ratio of a high-density WDM system can be degraded by Raman crosstalk. The worst case degradation is considered. Severe degradation is possible for systems with a large channel number and high transmitted signal level. The degradation may set a limit on the number of channels, the transmitted signal level, and the initial ON/OFF ratio.

Introduction: High-density wavelength-division-multiplexing (HDWDM) technique is a potential candidate for fully exploiting the vast bandwidth provided by singlemode fibres.[1] A limitation imposed on HDWDM systems is the crosstalk caused by stimulated Raman scattering (SRS). The Raman crosstalk arises from the mutual coupling of the multichannel signals through SRS. As a result, optical powers of the shorter wavelength channels are depleted by the longer wavelength channels so that the useful power of the shorter wavelength channels decreases. Previous investigations have concentrated on the power depletion of the shortest wavelength channel which might limit the number of channels or transmitted powers.[2,3] The ON/OFF ratio degradation which arises from SRS is considered. The idea stems from the fact that in pulse-modulated HDWDM systems, the transmitted power may not be zero in the 'OFF' state due to nonzero bias current of the signal laser which is generally used to accelerate switching speed. Hence there is a finite ON/OFF ratio at the transmitting end. The ON/OFF ratio of the signals can be degraded due to Raman crosstalk, particularly for the shortest and the longest wavelength channels. The ON/OFF ratio degradation of an HDWDM system due to Raman crosstalk as studied. The worst case is considered and shows that the ON/OFF ratio can be seriously degraded for systems with large number of channels and high transmitted signal level.

Analysis: The propagation of an intensity modulated N-channel HDWDM fibre transmission system is analysed by considering SRS. Let A and α denote the effective core area and loss coefficient of the fibre, respectively. Assume a $6\,\mu m$ effective core diameter and take α as 0·2 dB/km. To approximate the practical Raman gain profile in fibres, a piecewise linear function is used to simulate the measured gain profile,[4] and the Raman gain peak is taken as 8×10^{-4} m/W.

Since the signal linewidths of an HDWDM system are usually much smaller than the bandwidth of the Raman gain profile the Raman gain for a signal channel can be assumed to be constant. The Raman gain constant coupling the ith and mth signal channels, g_{im}, can then be obtained from the piecewise linear function with an appropriate Raman shift.

Let the signal powers $S_i(0)$ ($i = 1, 2, \ldots, N$) be injected at $z = 0$ and travel in the $+z$ direction. Assume the transmitted powers for the N channels are the equal with $S_i(0) = P_{on}$ in the 'ON' state and $S_i(0) = P_{off}$ in the 'OFF' state. In a pulse modulated HDWDM system, fibre dispersion can cause group velocity mismatch among the signal pulses which results in walk-off effect in the Raman processes. Here the case when the pulse duration is long enough so that the coupled equations can be treated as CW case[5] is taken for simplicity. The coupled equations governing the propagation of the multiwavelength signals are then formulated as

$$\frac{dS_i(z)}{dz} = \left[-\alpha + \sum_{j=1}^{i-1} \frac{g_{ji} S_i(z)}{2A} - \sum_{k=i+1}^{N} \frac{\nu_{si}}{\nu_{sk}} \frac{g_{ik} S_k(z)}{2A} \right] S_i(z) \qquad i = 1, 2, \ldots, N \quad (1)$$

where ν_{si} is the lightwave frequency of the ith channel. We assume $\nu_{s1} > \nu_{s2}, \ldots, > \nu_{sN}$ and the N channels are equally spaced with channel spacing $\Delta\nu$. The factor 2 in the denominator accounts for the random polarisation of the signal waves. The first term denotes the fibre loss while the second and the third terms express the cross coupling among the signal channels. These cross coupling terms result in crosstalk among the signals. The shorter wavelength channels will thus be depleted by the longer wavelength channels.

From eqn. 1 it is apparent that channel 1 (CH 1) is the most depleted channel while channel N (CH N) obtains most power from the other channels. The worst case ON/OFF ratio for these two extreme channels is considered. The worst case ON/OFF ratio is taken as the ratio of the minimum signal power in the 'ON' state to the maximum in the 'OFF' state. When $S_1(0) = P_{off}$, since CH 1 is depleted by the other channels the maximum signal power occurs when all the other channels are also 'OFF' so that the depleted power of CH 1 is minimum. In this case, since the signal levels are low, their cross couplings are expected to be negligible such that

$$S_1(0) \simeq P_{off} e^{-\alpha z} \quad (2)$$

When $S_1(0) = P_{on}$, the minimum signal power occurs when all the other channels are in the 'ON' state so that CH 1 is mostly depleted. And the worst case ON/OFF ratio of CH 1 is written as

$$R_1(z) = 10 \log \frac{S_1^*(z)}{P_{off} e^{-\alpha z}} \quad (3)$$

where $S_1^*(z)$ is the minimum signal power of CH 1 in the 'ON' state which can be numerically obtained from eqn. 1 with $S_i(0) = P_{on}, i = 1, 2, \ldots, N$.

On the other hand for CH N, since it obtains powers from the other channels, the minimum signal power for $S_N(0) = P_{on}$ occurs when all the other channels are 'OFF'. Again there is negligible cross coupling so that

$$S_N(z) \simeq P_{on} e^{-\alpha z} \quad (4)$$

and when $S_N(0) = P_{off}$, the maximum signal power occurs when all the other channels are 'ON'. Then the worst case ON/OFF ratio of CH N is given as

$$R_N(z) = 10 \log \frac{P_{on} e^{-\alpha z}}{S_N^*(z)} \quad (5)$$

where $S_N^*(z)$ is the maximum signal power for CH N in the 'OFF' state which can be numerically obtained from eqn. 1 with $S_i(0) = P_{on}$, $i = 1, 2, \ldots, N - 1$, and $S_N(0) = P_{off}$.

The relation between $R_i's$ and the fibre length is shown in Fig. 1. Because Raman interaction mainly occurs in the high power region, $R_i's$ degrade faster in the region near the transmission end and reach a constant value at the far end. We also see that CH 1 experiences more degradation than CH N. Let R_0 denote the initial ON/OFF ratio (in dB) at $z = 0$, we can further define the ON/OFF ratio degradation at $z = L$ with respect to R_0 as

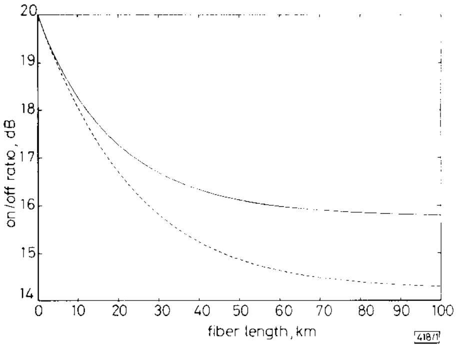

Fig. 1 *ON/OFF ratio against fibre length*

$N = 40$; $\Delta\nu = 2$ nm; $P_{on} = 5$ dBm

---- CH 1

—— CH N

$$D_i = R_0 - R_i(L) \qquad (6)$$

where $i = 1$ and N correspond to CH 1 and CH N, respectively. Inspection of Fig. 2 reveals that D_i increases with the number of channels because of the enhancement of Raman crosstalk as the channel number increases. It can be seen that the degradation of CH 1 is always larger than CH N and over 10 dB degradation is possible for $N = 50$. This serious degradation can limit the number of channels. D_1 with respect to P_{on} is plotted in Fig. 3. This Figure shows that D_1 increases with P_{on} since Raman interaction increases. For small transmitted signal level, there is negligible ON/OFF ratio degradation. However, D_1 increases rapidly for large P_{on}. For $P_{on} = 10$ dBm and $N = 40$, a very serious degradation occurs which results in 22 dB degradation. Note that the initial ON/OFF ratio R_0 is 25 dB, a 22 dB degradation means that the worst case ON/OFF ratio at the far end is 3 dB. This is an unacceptable situation. The degradation is reduced to 12 dB for $N = 30$. The serious ON/OFF ratio degradation can limit the transmitted signal power and number of channels. One can reduce the ON/OFF ratio degradation by limiting the transmitted signal to a lower level. This will decrease the system transmission distance. On the other hand, one can increase the initial ON/OFF ratio such that the ON/OFF ratio at the receiving end is acceptable.

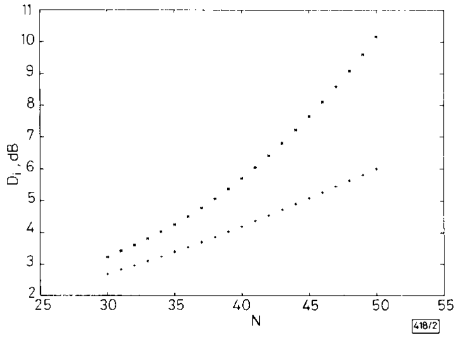

Fig. 2 *Relation between D_i and number of channels*

$L = 100$ km; $\Delta\nu = 2$ nm; $P_{on} = 5$ dBm; $P_{off} = -20$ dBm

• D_1

+ D_N

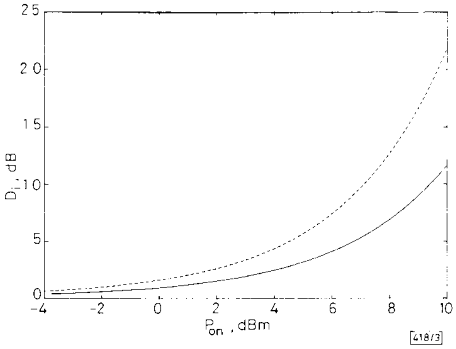

Fig. 3 *Relation between D_1 and P_{on}*

$L = 100$ km; $\nu = 2$ nm; $R_0 = 25$ dB

---- $N = 40$

—— $N = 30$

In conclusion we have investigated the ON/OFF ratio degradation of an HDWDM system by considering Raman crosstalk. The worst case ON/OFF ratio degradation for the shortest and the longest wavelength channels are analysed. We find that the shortest wavelength channel experiences larger degradation may occur for systems with large channel number and high transmitted signal level.

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LOW LOSS OPTICAL RIDGE WAVEGUIDES IN A STRAINED GeSi EPITAXIAL LAYER GROWN ON SILICON

Indexing terms: Optoelectronics, Optical waveguides, Silicon

The realisation of single-mode ridge waveguides in a strained $Si_{1-x}Ge_x$ epitaxial layer grown on silicon by MBE is reported. Measurements at $\lambda = 1{\cdot}3\,\mu m$ yield a refractive index enhancement of $2{\cdot}2 \times 10^{-3}$ for $x = 0{\cdot}01$ and waveguide losses around 3–5 dB/cm.

Introduction: There is a growing interest in the $Si_{1-x}Ge_x$ material system, especially for fast heterojunction bipolar transistors.[1,2] $Si_{1-x}Ge_x$ is also an attractive candidate for optoelectronics. Photodiodes and optical waveguides have both been realised.[3–6] Single-mode waveguides in SiGe were first demonstrated in Reference 6 where an indiffusion of Ge into