RF signal back to 10 dBm (for a gain of unity) during steering of the phased array.

Fig. 3 shows the RF insertion phase (angular part of S_{21}) between the input and output ports as the RF input

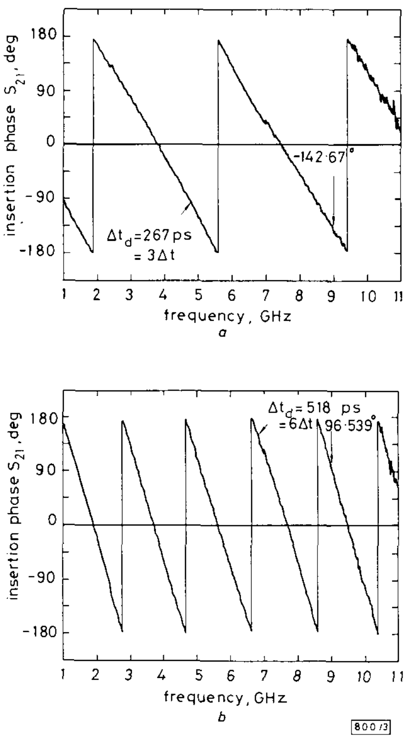

Fig. 3 *Differential phase (a) $\phi_5 - \phi_8$ between channels 5 and 8 and (b) $\phi_2 - \phi_8$ obtained between channels 2 and 8 by sweeping from 1 to 11 GHz*

(= +10 dBm) was swept from 1 to 11 GHz. During the measurement, the reference channel of the network analyser was first adjusted in length to cancel the phase slope due to the shortest delay line. Thus, the insertion phase obtained for subsequent channels represents the differential phase ($\Delta\phi = \phi_i - \phi_8$, $i = 1, \ldots, 7$) measured with respect to the shortest delay line (channel 8). Specifically, the difference in time delay Δt_d between a particular line and the shortest line is given by $\Delta t_d = (\Delta\phi/\Delta f)/360°$, where Δf is the corresponding frequency sweep. From the slopes of the insertion phase measurement shown in Fig. 3*a*, we obtain a Δt_d of 267 ps for channel 5, which is approximately 3 times Δt ($\sim$88 ps). The slope of channel 2 is twice that of channel 5, and corresponds to a differential time delay of 518 ps, which is $\sim 6\ \Delta t$. The differential time delay thus calculated agrees exactly with that estimated from the propagation time difference between the fibres for all seven channels.

Fig. 3 indicates that although the signal/noise ratio of the differential phase was slightly degraded by the high-frequency roll-off in the laser modulation response, excellent phase linearity was maintained from 1 to 11 GHz. The modulation response of semiconductor lasers follows a second-order transfer function[2] which predicts a phase change of $-\pi$ for its angular component from DC to high frequencies. In particular, a sharp transition occurs at the resonance frequency. The width of the sharp transition is approximately γ, where γ, given by $I/(I_{th}\tau_s)$ for a laser with carrier lifetime τ_s, is the damping constant of the second-order transfer function. Since the resonance frequencies of the lasers lay within our range of frequency sweep for the differential phase measurements, the linearity of the differential phase will suffer if the lasers that addressed the channels being compared exhibit widely separated resonance frequencies. Such nonlinearities in the differential phase were indeed observed if the resonance frequency of one laser was 'detuned' from the other deliberately. We accomplished broadband differential phase linearity for the time-shifter by biasing the lasers so that their resonance frequencies coincided at $\sim$7 GHz.

In summary, we have demonstrated a broadband 3-bit fibre-optic delay network for steering phased array antennas. The delay increments were implemented by switching the bias currents of the lasers pigtailed to the optical delay lines. By ensuring uniformity in the modulation response of the lasers driving the 8 channels, we achieved excellent linearity for the differential insertion phase from 1 to 11 GHz.

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HIGH-DENSITY WDM SYSTEMS USING POST-TRANSMITTER FIBRE RAMAN AMPLIFIER TO RELAX RAMAN CROSSTALK LIMITATION

Indexing terms: Optical communications, Multiplexing, Optical fibres, Nonlinear optics

The limitation of transmission distance imposed by Raman crosstalk in a high-density WDM system is numerically analysed. We introduce a post-transmitter fibre Raman amplifier to relax this limitation. The examples show that the limitation can be relaxed by 7 dB and 15 dB amplifier gain is obtainable. In addition, a much lower transmitted power level can be used to obtain the maximum transmission distance.

Introduction: Optical nonlinearities can lead to undesirable power loss and signal distortion in optical communication systems. Among these, stimulated Raman scattering (SRS) with its broad gain profile is known to be a critical limitation to fibre systems. In a multichannel system, since the stimulated Raman signals arise from launched signal light instead of weak spontaneous emission noises, SRS is enhanced, which causes crosstalk among the channels and degrades system performance.[1] In a high-density wavelength-division-multiplexed (HDWDM) system where several tens of wavelength channels are multiplexed into an optical fibre, the power depletion of shorter wavelength channels due to SRS is expected to limit the system transmission distance. On the other hand, SRS can be employed as direct optical amplification, called a fibre Raman amplifier, to amplify simultaneously multichannel signals, which is of special interest in an HDWDM system.[2] Here we discuss the Raman crosstalk limitation and intend to relax it by using a post-transmitter fibre Raman amplifier (PTFRA).

Analysis and discussion: To simplify the analysis, a Lorentzian Raman gain profile is taken to approximate the actual gain shape in fibres,[3] given as

$$g(\nu_R) = \frac{g_0(w/2)^2}{(\nu_R - \nu_0)^2 + (w/2)^2} \quad (1)$$

where g_0 is the peak Raman gain coefficient, w is the full width at half-maximum of the Lorentzian lineshape, ν_R is the Raman shift between the two coupling waves, and ν_0 is the Raman shift corresponding to the peak gain.

We deal with the crosstalk caused by SRS in an N-channel HDWDM system in which the signal powers $S_i(0)$ ($i = 1, 2, \ldots, N$) are injected at $z = 0$ and propagate along the $+z$ direction. We assume that all the signals are pulse-modulated and all the channels are in the 'ON' state. Considering SRS, we may formulate the differential equations which govern the signal propagation as

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

where A and α_s denote the effective Raman cross-section and the loss coefficient of the signals, respectively. We assume the channels are equally spaced with channel spacing $\Delta\nu$ and $\nu_{s1} > \nu_{s2} > \ldots > \nu_{sN}$; g_{mn} is the Raman gain constant coupling the mth and nth signals which can be calculated from eqn. 1 with $\nu_R = \nu_{sm} - \nu_{sn}$. The factor 2 in the denominator accounts for the random polarisation of the signal waves.[4] The second term on the right-hand side of eqn. 2 expresses the obtained power of the ith channel from those shorter wavelength channels, and the third term accounts for the depleted power by the longer wavelength channels. Here we consider that the signal power of each channel is the same, i.e. $S_i(0) = S_0$, for $1 \le i \le N$. Thus the shortest wavelength channel (channel 1) will be mostly depleted by the other channels and becomes the least-power channel at a distance L from $z = 0$. As a result, the system transmission distance will be limited by channel 1. To obtain the signal powers at $z = L$, eqn. 2 is numerically solved. We see, as shown in Fig. 1, the received power of channel 1 at $z = L[S_1(L)]$ departs from the linear loss curve due to Raman crosstalk. The departure increases with S_0 because SRS is enhanced as the transmitted power increases. In addition, there exists a maximum value for $S_1(L)$. As S_0 increases beyond this value, the depleted power of channel 1 due to Raman crosstalk is larger than that increased at the transmitting end, so that $S_1(L)$ decreases. Hence the maximum achievable system transmission distance is limited.

In an effort to relax the Raman crosstalk limitation, we introduce PTFRA by employing a strong continuous pump wave at the transmitting end to amplify the multiwavelength signals. Taking advantage of the long range amplification characteristic of the fibre Raman amplifier, we can gradually compensate for the depleted power of the shorter wavelength channels through the pump so as to relax the Raman crosstalk limitation. Therefore, the system transmission distance can be extended. With a strong pump power $P(0)$ injected at $z = 0$, the coupling equations governing the signals and the pump propagation become

$$\frac{dS_i(z)}{dz} = \left[-\alpha_s + \frac{g_i}{2A} P(z) + \sum_{j=1}^{i-1} \frac{g_{ij} S_j(z)}{2A} - \sum_{k=i+1}^{N} \frac{\nu_{si}}{\nu_{sk}} \frac{g_{ik} S_k(z)}{2A} \right] S_i(z) \qquad i = 1, 2, \ldots, N \quad (3)$$

$$\frac{dP(z)}{dz} = -\left[\alpha_p + \sum_{i=1}^{N} \frac{\nu_p}{\nu_{si}} \frac{g_i S_i(z)}{2A} \right] P(z) \quad (4)$$

where g_i is the Raman gain constant coupling the pump and the ith channel which can be obtained from eqn. 1 with $\nu_R = \nu_p - \nu_{si}$, and α_p denotes the loss constant of the pump. Since channel 1 is depleted most by the other channels, we place it at the Raman gain peak of the pump, i.e. $\nu_0 = \nu_p - \nu_{s1}$. With such an arrangement, because g_1 is the largest among the g_is we expect that channel 1 can obtain much power from the pump via SRS, so that it may no longer be the least-power channel at $z = L$. Since the transmission distance is limited by the least-power channel, we show in Fig. 2 the received power of the least-power channel at $z = L$ as a function of S_0 with and without a PTFRA. Inspection of the Figure reveals that the application of PTFRA can extend the maximum received power of the least-power channel from -17 to -10 dBm, which shows 7 dB relaxation. In addition, the maximum point with a PTFRA is achieved at $S_0 = -4$ dBm, which is much lower than that obtained at $S_0 = 6$ dBm without a PTFRA. Thus we conclude that the use of PTFRA not only relaxes the Raman crosstalk limitation but also achieves greater received signal power, and in turn longer system transmission distance at a much lower transmitted power level. We further observe that about -10 and -25 dBm signal powers can be received at $z = L$ with and without a PTFRA when $S_0 = -4$ dBm. Thus 15 dB gain is achieved, corresponding to 60 km extended transmission distance for 0·25 dB/km fibre loss. Also note that for high transmitted signal power level, the PTFRA is of no use because the received power of the least-power channel may be less than that of without a PTFRA. Therefore the PTFRA is particularly suitable for an HDWDM system with limited transmitter power.

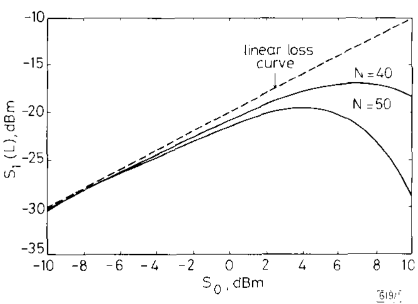

Fig. 1 *Received against transmitted signal power of channel 1*

For familiarity we use wavelength unit for $\Delta\nu$; $L = 80$ km, $\Delta\nu = 2$ nm, $\alpha_s = 0{\cdot}25$ dB/km, $A = 3 \times 10^{-11}$ m^2, $g_0 = 8 \times 10^{-14}$ m/W, $\nu_0 = 460$ cm^{-1}, $w = 240$ cm^{-1}

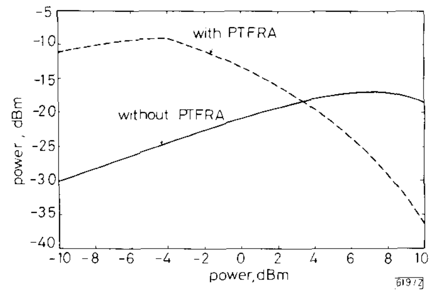

Fig. 2 *Received against transmitted signal power for least-power channel with and without PTFRA*

$\alpha_p = 0{\cdot}35$ dB/km, $L = 80$ km, $N = 40$, $\Delta\nu = 2$ nm, $P(0) = 1{\cdot}2$ W

Conclusion: In this letter we have studied the crosstalk limitation imposed by SRS on an HDWDM system. We provide a simple way to relax this limitation by introducing a strong pump power as a post-transmitter Raman amplifier to compensate for the depleted power of the shorter wavelength channels. The results show that the Raman crosstalk limitation can be relaxed by 7 dB with a PTFRA and long distance transmission is achievable at a much lower transmitted power level. The PTFRA is particularly useful if transmitter light powers are limited. Because of the simple configuration of PTFRA, we expect that it may be a potential candidate to relax the Raman crosstalk limitation in an HDWDM system.

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SBS THRESHOLD DEPENDENCE ON LINE CODING IN PHASE-MODULATED COHERENT OPTICAL SYSTEMS

Indexing terms: Optical communications, Phase modulation, Nonlinear optics, Codes

In this letter the dependence of the stimulated Brillouin threshold on the adopted line code in phase-modulated coherent optical systems is studied considering some of the most common line codes.

Introduction: Two main applications are foreseen in the future communication environment for optical coherent transmission systems: long-haul high-capacity links and multichannel FDM systems.

The technological developments in high-power, narrow-linewidth, single-mode semiconductor lasers and wide-band high-sensitivity coherent receivers lead to systems in which the main limitation to the maximum link length is constituted by nonlinear effects.

In particular in single-channel systems the most important nonlinear effect is stimulated Brillouin scattering (SBS). If the power launched in the fibre surpasses a threshold value, this effect causes a conversion of a great part of the signal power into a new generated wave (the Stokes field) that propagates back towards the transmitter.[1]

That induces an important limitation to the power that can be coupled into the fibre[2] and, in full duplex systems, can cause interference between the signals transmitted in the two directions.

The SBS threshold depends strongly on the transmitted signal modulation[3] and a great effort has been produced to find the modulation format that maximises it.

In this letter the SBS threshold is calculated for a phase-modulated signal, considering some of the most common line codes to analyse the effect of the code spectrum shape on SBS. In the adopted analytical model the SBS gain curve is calculated by the convolution between the code spectrum and the intrinsic Brillouin lineshape,[4,5] and the threshold power is obtained by the maximum value of the gain curve. Moreover a recently proposed method to estimate the convolution approximation accuracy[6] is used to validate the results.

Theory: In a coherent communication system the transmitted signal can be considered an ergodic stationary process characterised by its first-order probability density and by its power spectral density $S(\omega)$. In this condition it is possible to demonstrate[5] that the baseband Brillouin gain curve $G(\omega)$ can be approximately calculated by means of the following formula:

$$G(\omega) = \frac{gL_e}{A_e} \int_{-\infty}^{\infty} S(\omega - \xi) \frac{d\xi}{1 + (\xi/\Gamma)^2} \quad (1)$$

where g is the fibre characteristic gain, A_e is the mode effective area, L_e is the fibre effective length[3] that for long links tends to the inverse of the fibre attenuation, and Γ is the intrinsic Brillouin linewidth (HWHM).

A procedure to estimate the approximation error has been stated[5] by taking into account the interference between the pump and the Stokes spectral components. Moreover the method validity has been confirmed experimentally for PSK modulation.[6] Starting from $G(\omega)$, and in particular from its maximum value G_{max}, the SBS threshold P_{th} is given by

$$P_{th} = 21 \frac{A_e}{L_e G_{max}} \quad (2)$$

The transmitted signal spectrum is given by[7]

$$S(\omega) = \int_{-\infty}^{\infty} |F(\omega - \xi)|^2 C(\omega - \xi) L(\xi)\, d\xi \quad (3)$$

where $F(\omega)$ is the Fourier transform of the transmitted pulse shape, $C(\omega)$ is the line code autocorrelation function transform and $L(\omega)$ is the transmitting laser lineshape.

From the above equations the SBS dependence on the spectrum of the adopted line code can be evaluated.

Results: To evaluate the influence of the line code on SBS threshold in phase-modulated coherent systems, 12 common line codes are selected, a perfectly monochromatic transmitting laser is assumed and an ideal rectangular transmitted pulse is supposed.

A finite transmitting laser linewidth can be easily taken into account if its lineshape is supposed Lorentzian. In this condition, substituting eqn. 3 into eqn. 1 the convolution product between the laser and the Brillouin lineshapes can be obtained. It results in a Lorentzian function whose width is the sum of the convolution factor widths. This allows us to assume an effective Brillouin bandwidth equal to $\Gamma + B_L$, where B_L is the laser linewidth, and to assume again a monochromatic transmitting laser.

The following values of the relevant physical parameters are assumed: $g = 2{\cdot}2 \times 10^{-11}$ m/W, $A_e = 1{\cdot}32 \times 10^{-10}$ m^2, $L_e = 6679$ m, $\Gamma/\pi = 35$ MHz. These are the measured values of a 10 km dispersion-shifted single-mode fibre with an attenuation of 0·2 dB/km for which the CW threshold is 18·9 mW.[6]

The calculated threshold values are reported in Table 1 for

Table 1 STIMULATED BRILLOUIN SCATTERING THRESHOLD FOR DIFFERENT LINE CODES AT BIT RATES R = 140 AND 565 Mbit/s

	SBS threshold	
Code	140 Mbit/s	565 Mbit/s
	mW	mW
NRZ	38·1	112·6
AMI	48·7	120·4
B6ZS	48·9	123·5
HDB3	48·7	116·7
PST Mod	47·9	127·9
4B-3T	41·8	118·1
FOMOT	43·6	124·6
MS43	45·4	131·2
DM	44·8	92·2
CMI	38·3	79·8
3B4B	40·9	91·3
5B6B	40·6	113·4