variation owing to changes in signal power is decided by the response time of the Kerr effect of silica fibre, which is ultrafast below picosecond level. This implies that the use of PSAs as repeater amplifiers will expand the electrical regenerative repeater spacing in ulfrafast transmission systems.

Conclusion: An unsaturated gain of 23dB was obtained from a PSA using a zero-dispersion fibre in a nonlinear loop mirror. Gain saturation was first confirmed in PSAs and the excess amplitude noise in the input signal was suppressed in the PSA operating as a limiting amplifier.

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OTDR pulse power limit in on-line monitoring of optical fibres owing to stimulated Raman scattering

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Indexing terms: Optical time-domain reflectometry, Optical fibres

If a singlemode fibre is monitored with an optical time-domain reflectometer (OTDR) at 1.65μm, stimulated Raman scattering causes nonlinear loss for a transmission channel at 1.55μm. Calculations show that in some cases the permitted OTDR pulse power is limited to a few milliwatts.

Introduction: On-line monitoring of singlemode fibre (SMF) links operating at 1.55μm with an 1.65μm optical time-domain reflectometer (OTDR) is promising because of its ability to detect channel degradations before transmission quality decreases [1]. It also offers surveillance of optical fibres independent of the transmission format. It was reported [1, 2] that, owing to the use of optical filters and wavelength division multiplexers, the on-line measurement did not affect the transmission, although fibre nonlinearities were not considered. Owing to a large OTDR peak power leading to a good dynamic range with good spatial resolution several attempts were made to increase the available peak power at 1.65μm still making use of the laser diode technology. Diodes with peak powers of 15dBm are commercially available and using optical amplification >24dBm can be achieved [3]. The calculations presented in this Letter predict an upper limit of the permitted OTDR pulse power for in-service measurement owing to the nonlinear interaction between the signal bearing lightwave and the monitoring pulses caused by stimulated Raman scattering (SRS). Exceeding this OTDR power limit leads to an excessive time-dependent loss for the transmission signal at 1.55μm.

Theory of CW SRS: In the CW case the interaction between the Stokes power P_S and the pump power P_p through SRS is governed by the following pair of coupled equations:

$$\frac{dP_S}{dz} = -\alpha_S P_S + \frac{g_R}{A_{eff}} P_p P_S \qquad (1)$$

$$\frac{dP_p}{dz} = -\alpha_p P_p - \frac{\lambda_S}{\lambda_p}\frac{g_R}{A_{eff}} P_p P_S \qquad (2)$$

where α_S and α_p are attenuation coefficients, A_{eff} is an effective core area and g_R is the Raman coefficient which is a function of the wavelengths λ_S, λ_p and the polarisation maintaining properties of the fibre. For small pump powers the assumption $\alpha_S \gg (g_R/A_{eff})\cdot P_p$ is valid and the second term on the right hand side of eqn. 1 can be omitted. Using this nonamplified Stokes approximation eqns. 1 and 2 have the analytical solution

$$P_S(z) = P_{S0} e^{-\alpha_S z} \qquad (3)$$

$$P_p(z) = P_{p0} e^{-\alpha_p z} 10^{-a_{NL}/10} \qquad (4)$$

with

$$a_{NL} = 4.343 \frac{\lambda_S}{\lambda_p} g_R \frac{z_{eff}}{A_{eff}} P_{S0} \qquad (5)$$

where $z_{eff} = \alpha_S^{-1}(1-\exp(-\alpha_S z))$ is called the effective length, P_{S0} and P_{p0} are the incident powers at $z = 0$, and a_{NL} is an additional nonlinear loss through SRS in dB.

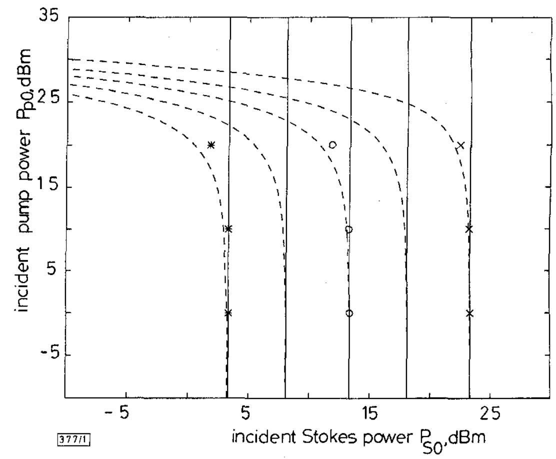

Fig. 1 *Nonlinear loss against incident Stokes and pump power*

——— nonamplified Stokes approximation
– – – – numerical solution of (1, 2)
✳, ○, × 0.1, 1, and 10dB eye closure of simulated 144Mbit/s NRZ transmission
Also shown: a_{NL} = 0.3 and 3dB

For a SMF with λ_S = 1.65μm, λ_P = 1.55μm, $\alpha_S = 5.8\cdot10^{-5}$m^{-1} (0.25dB/km), $\alpha_p = 4.6\cdot10^{-5}$m^{-1} (0.2dB/km), $g_R = 2.9\cdot10^{-5}$W^{-1}m (assuming completely scrambled polarisations of the two waves), A_{eff} = 50μm² and $z_{eff} = \alpha_S^{-1}$ = 17.3km Fig. 1 shows for which combinations of P_{S0} and P_{p0} a nonlinear loss a_{NL} of 0.1, 0.3, 1, 3 and 10dB occurs. Together with the straight vertical lines of the nonamplified Stokes approximation there are the contours of the exact numerical solution of eqns. 1 and 2. It can be seen that the approximation is valid for pump powers P_{p0} up to 10dBm. For pump powers approaching the Raman threshold ($P_{p0} \simeq$ 32dBm for the given values [4], p. 223) the loss gets very high, hence most of the pump power is transferred to the Stokes wave.

SRS in monitoring systems: In the monitoring system under consideration rectangular OTDR pulses acting as a Stokes wave propagate in the same direction as a transmission signal acting as a pump wave. Therefore the nonlinear loss is time-dependent and only that part of the transmission signal which copropagates with the OTDR pulse is depleted. For typical values like an OTDR pulsewidth of 1μs (~100m of spatial resolution), an OTDR repetition time of 500μs, a group delay mismatch per unit length of

2.5ns/km and a fibre length of 40km, this results in the maximum nonlinear loss in only 0.18% of the time. For the rest of the time the transmission signal is less depleted or nondepleted.

Neglecting group-velocity dispersion (GVD), it can be shown that, owing to the large bandwidth of the SRS effect (~2.4THz) even for high speed transmission systems, the nonlinear signal loss can be calculated from the CW case. The nonlinear loss for an incident transmission power $P_{p0}(t)$ is then a function of the incident OTDR power $P_{S0}(t)$ at the same moment and can be calculated by solving eqns. 1 and 2. If the optical power of the transmission signal is modulated this results in a signal-dependent loss for transmission peak powers >10dBm (see Fig. 1).

Taking a large degree of GVD into account, the loss for a single short transmission pulse, copropagating the entire fibre length with the longer OTDR pulse, is described by the nonamplified Stokes approximation. This is because through pulse walkoff the amplified part of the OTDR pulse is not interacting with the data pulse for long.

As a result all the pulses of an on-off-keying (OOK) signal, copropagating the whole fibre length with the OTDR pulse, are attenuated by a value which lies in-between the exact CW solution and the nonamplified Stokes approximation. The actual attenuation is a function of the preceding (for anomalous dispersion) bit pattern and the degree of GVD. Therefore in the bit pattern ...000001 the trailing '1' has got the lowest loss and in ...111111 it has got the highest loss. As can be seen in Fig. 1 for low transmission powers P_{p0}, there is no bit pattern dependence of the loss, hence a_{NL} can be calculated from eqn. 5.

Simulations: The applicability of the CW formalism to the monitoring system was verified by simulation of a 144Mbit/s NRZ OOK transmission of a pseudo-random binary sequence with the coupled amplitude equations for the Stokes and pump fields (A_S, A_p) [4, p. 225]:

$$\frac{\partial A_S}{\partial z} + \frac{1}{v_{gS}}\frac{\partial A_S}{\partial t} + \frac{i}{2}\beta_{2S}\frac{\partial^2 A_S}{\partial t^2} + \frac{\alpha_S}{2}A_S = i\gamma_S(|A_S|^2 + 2|A_p|^2)A_S + \frac{g_R}{2A_{eff}}|A_p|^2 A_S \quad (6)$$

$$\frac{\partial A_p}{\partial z} + \frac{1}{v_{gp}}\frac{\partial A_p}{\partial t} + \frac{i}{2}\beta_{2p}\frac{\partial^2 A_p}{\partial t^2} + \frac{\alpha_p}{2}A_p = i\gamma_p(|A_p|^2 + 2|A_S|^2)A_p - \frac{g_R}{2A_{eff}}\frac{\lambda_S}{\lambda_p}|A_S|^2 A_p \quad (7)$$

Besides SRS, the nonlinear effects of self-phase modulation and cross-phase modulation are included through the coefficients γ_S and γ_p. GVD is considered by the group delay mismatch per unit length $\Delta\tau = v_{gp}^{-1} - v_{gS}^{-1}$ and the dispersion coefficients β_{2S} and β_{2p}. With $\lambda_S = 1.65\mu m$, $\lambda_p = 1.5\mu m$, $\alpha_S = 5.8 \cdot 10^{-5} m^{-1}$, $\alpha_p = 4.6 \cdot 10^{-5} m^{-1}$, $g_R = 2.9 \cdot 10^{-14}\ W^{-1}m$, $A_{eff} = 50\mu m^2$, $\Delta\tau = 2.5 ns km^{-1}$, $\gamma_S = 2.4 W^{-1}km^{-1}$, $\gamma_p = 2.6 W^{-1}km^{-1}$, $\beta_{2S} = -48 ps2km^{-1}$, $_{\beta 2p} = -20 ps^2km^{-1}$ and an OTDR pulsewidth of 1μs the eye closures for different OTDR peak powers were determined and showed excellent agreement to the CW formulas. For the eye closures (defined as the ratio of the eye openings in the receiver with and without OTDR pulses) of 0.1, 1 and 10dB the simulation results are included in Fig. 1.

Application to WDM and PON systems: Though eqns. 1, 2, 6 and 7 are strictly valid only for a two channel system with monochromatic waves, the results can also be applied to wavelength-division-multiplex (WDM) systems or longitudinal-multimode lasers, provided that the spectral width of the transmission and the monitoring channel is small compared to their spectral separation (≃100). The resulting loss can be calculated from the total powers in the two channels. Under this aspect total transmission powers >10dBm can easily be achieved.

If a point-to-multipoint and not a point-to-point structure, realised by a passive optical network (PON), is to be monitored, the nonlinear loss of the first fibre section ahead of the first optical splitter often dominates the nonlinear loss of the following network. Since this section is usually only a few kilometres long, this results in much higher allowed power levels for the OTDR pulses.

Conclusions: Large peak power of OTDR pulses in on-line monitoring systems lead to a time-periodic loss for the transmission channel in the 1.55μm region. To conserve the advantage of independence of the actual transmission format a low nonlinear loss a_{NL} must be demanded: ~8dBm as maximum allowed OTDR peak power can be calculated from eqn. 5 for a_{NL} = 0.3dB. For analogue transmission systems even this value, which corresponds to a 7% amplitude breakdown of the electrical signal, might be too high. For applications, using transmission powers >10dBm, it must be kept in mind that a_{NL} given through eqn. 5 is only a lower limit for the nonlinear loss.

To conclude, an increase in the dynamic range or spatial resolution for on-line monitoring systems has to be obtained by other means than the enlargement of OTDR peak power above the limit given by eqn. 5.

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Polarisation mode dispersion: Large scale comparison of Jones matrix eigenanalysis against interferometric measurement techniques

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Indexing terms: Optical fibres, Optical dispersion

A comparison of polarisation mode dispersion (PMD) measurements between the Jones matrix eigenanalysis and the interferometric technique is presented. A large range of PMD delays between 0.1 and 20ps have been taken into account. The results show a very good agreement in the range up to 5ps. The slope of a linear fit deviates <3% from unity. Taking into account the values in the higher range up to 20ps, a deviation of 13% from unity is obtained.

Polarisation mode dispersion (PMD) is presently an important parameter for optical fibres and cables. Indeed, because of the limitations it imposes on digital and on analogue transmissions, there is an urgent industrial need for a practical definition of PMD, standard measurement techniques [1] and recommended maximum values for fibres and/or cables. Consequently, PMD is very actively discussed by all major standardisation bodies [2, 3]. These discussions are made more difficult by the random nature of PMD. Hence, even the specialists do not fully agree on the relations between the various aspects of PMD and the corresponding different measurement schemes. In this Letter, we set aside the theoretical debate [4–7] and concentrate on more than 150 experimental results, comparing two of the main measurement techniques currently under discussion in the standardisation bodies: the Jones matrix eigenanalysis (JME) [8, 9] and interferometric analysis [10, 11]. All these results were obtained in the last three years using two commercially available instruments.

The JME measurement scheme obtains data in the frequency (wavelength) domain, whereas the interferometric scheme obtains data in the time domain. Our results thus provide a useful comparison between the frequency and the time domain picture of PMD as well [7, 12]. For the JME measurements, two lasers