a pixel array image and then calculate the sum of absolute values of the cosine transform coefficients

$$I(z) = \sum_{u=u_1}^{u_2} |C(u, z)|$$

(where $0 < u_1 < u_2 < N - 1$) and the maximum value of $I(z)$ will deliver the best focusing.

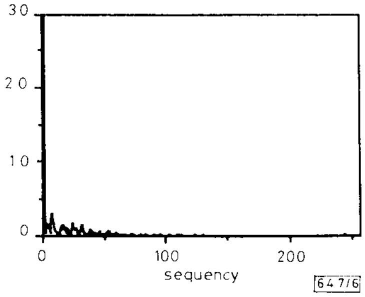

Fig. 6 *Absolute value of DCT coefficients computed from vague image of Fig. 4*

The following experiment was performed in the laboratory. We constructed a bandpass filter which confines the sequencies between u_1 and u_2 and then integrated the weight function between these two limits by moving the camera on the z axis, which is perpendicular on the plane. We plotted the curve in Fig. 7. This curve shows that from a certain threshold value, an image is obtained which is more or less sharp between z_1 and z_3.

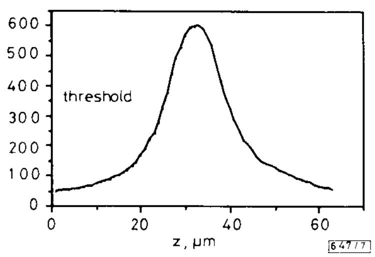

Fig. 7 *Values of absolute sum of DCT image pixel between sequency 2 and 128 from 256 pixels, when camera moves on z axis*

It must be emphasised that the intensity of the curve above does not correspond to an integral on the complete image, but rather on a part of the image which in our case corresponds to a half horizontal line of the image. If the image represents an object in relief (in three dimensions), we could have several different planes (parallel to the plane of image) corresponding to the sharp images. Each image corresponds to a precise depth plane which contains a certain number of points belonging to the object. To seek a precise image plane, it is enough to perform some calculations on a block size of $M \times N$ pixels belonging to this plane.

If we return to the curve above, we notice that the position z_2 corresponds to a global maximum for the integral function, which corresponds to the optimum focus position of the image, that is to say, to the position of the camera which gives the sharpest image.

Possible uses for presented method: The autofocusing criterion described above can be used for tuning an optical device in applying the criterion to some points of the image that can be chosen according to the application. Thus it can be used for three-dimensional shape determination. Indeed if we apply this method to a small number of adjacent points in an image (an image array can be segmented into blocks of size $M \times N$ and 2-D transforms taken separately and independently in each block to produce the DCT blocks) we can determine the depth of this point, that is, the distance between the point and the image capture. We may apply an algorithm to any pixel and thus determine the shape of the object. The performance of this method depends, among other things, on the performance of the algorithm. Another application that could be developed, is edge detection with threshold and tracking of points of important magnitude.

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EXTINCTION RATIO DEGRADATION IN RAMAN AMPLIFIED OPTICAL COMMUNICATION SYSTEM

Indexing terms: Optical communication, Optical fibres

The extinction ratio of a Raman amplified optical fibre system is investigated. The results show that serious extinction ratio degradation occurs at high pump level. Because the Raman gain increases with pump power, there exists a trade-off between the extinction ratio and the achievable amplifier gain. A design rule to estimate the suitable pump power is presented.

Introduction: Optical amplification using stimulated Raman scattering is a possible means to extend communication distance.[1] A fibre Raman amplifier (FRA) can be used as a repeater amplifier to boost weak signals or a power amplifier at the transmitting end to further extend transmission distance.

Usually in an intensity modulated fibre system, the light source is not completely turned off in the OFF state due to nonzero biasing which is adopted to accelerate switching speed and reduce overshooting. Thus we have a finite extinction ratio at the transmitting end. The extinction ratio is of importance in determining system bit error probability.[2] When FRA is used, in addition to the amplified spontaneously scattered power (ASSP), the nonzero signal power in the OFF state is also amplified which can degrade the extinction ratio at the receiving end thus increase bit error probability. Here we estimate the extinction ratio of a Raman amplified fibre system and provide a simple rule to choose the suitable pump power to achieve an acceptable extinction ratio degradation.

Analysis: Consider a signal with initial power $S(0)$ and a pump with initial power $P(0)$ that are injected into a single-mode fibre at $z = 0$ and travel along the $+z$ direction. Owing to the nonlinearity of the fibre, the two waves can be mutually coupled through stimulated Raman scattering. The Raman process manifests itself as the power transfer from the high frequency wave to the low frequency one. If the pump frequency v_p is chosen to be higher than that of the signal v_s, the signal obtains power from the pump through stimulated Raman scattering; in other words, the signal is amplified by the pump. The signal and pump powers along the fibre are described by the coupled equations as

$$\frac{dS(z)}{dz} = -\alpha S(z) + \frac{g_0}{2A} P(z)S(z) + hv_{sp} \frac{g(v_p - v_{sp})}{2A} P(z) \quad (1)$$

$$\frac{dP(z)}{dz} = -\alpha P(z) - \frac{v_p}{v_s} \frac{g_0}{2A} P(z)S(z) \quad (2)$$

where $P(z)$ and $S(z)$ denote the pump and the signal powers, α is the fibre loss constant, g_0 is the Raman gain constant, and A is the effective Raman cross-section. The factor 2 accounts for the random polarisation of the two waves.[3] The Raman gain constant is a function of frequency shift between the pump and the signal.[4] Here we choose the pump frequency such that the signal obtains the maximum gain constant g_0. v_{sp} is the frequency of a longitudinal spontaneous emission mode and $g(v_p - v_{sp})$ is the corresponding gain constant which is a function of the frequency shift between the pump and the spontaneous emission mode.

The coupled equations can be analytically solved,[5] and written as

$$P(z) = \frac{P(0) \cdot e^{-\alpha z}}{1 + \xi + \eta} \quad (3)$$

$$S(z) = \frac{v_s}{v_p} P(0) \cdot e^{-\alpha z} \frac{\xi + \eta}{1 + \xi + \eta} \quad (4)$$

with

$$\xi = \frac{v_p S(0)}{v_s P(0)} \exp\left[K(1 - e^{-\alpha z})\right] \quad (5)$$

$$\eta = \frac{hv_p B_{eff}}{P(0)} \exp\left[K(1 - e^{-\alpha z})\right] \quad (6)$$

$$K = \frac{g_0 P(0)}{2\alpha A} \quad (7)$$

where h is the Planck constant and B_{eff} is the effective bandwidth of the ASSP which can be calculated from the Raman gain profile. Here we assume $P(0) \gg S(0)$.

$S(z)$ consists of two contributions: one is the injected signal amplified by the FRA, the other is the ASSP. Let $S(0) = S_{on}$ in the ON state and $S(0) = S_{off}$ in the OFF state, respectively. We define the extinction ratio of the signal along the fibre as

$$\gamma(z) = \frac{S(z)|_{S(0)=S_{on}}}{S(z)|_{S(0)=S_{off}}} \quad (8)$$

which is the ratio of the signal power in the ON state to that in the OFF state. Ideally, the transmitter laser should have zero output in the OFF state, i.e. $S_{off} = 0$ and $\gamma(0) = \infty$. Practically, there is output in the OFF state due to nonzero biasing; therefore we have a finite extinction ratio at $z = 0$.

Discussion and conclusion: We at first consider the case that an FRA is used as a transmitter power amplifier and take $S_{on} =$ 1 mW. The variation of γ along the fibre for several pump powers is shown in Fig. 1. We see that γ is degraded by the FRA because of the amplified signal in the OFF state and the generation of ASSP. The degradation is small at low pump power but serious degradation occurs at high pump level. For example, γ almost degrades to 0 dB at the far end for $P(0) = 0{\cdot}5$ W, which means that the signals nearly have the same powers in the ON and OFF states. The variation of signal power along the fibre with 0·5 W pump power is shown in Fig. 2. It is observed that the pump is significantly depleted by the signal either in the ON or OFF states and the signals in both states are amplified to about the same level and thus γ reduces to 0 dB.

The above results indicate that to have an acceptable extinction ratio at the far end we should keep the pump power

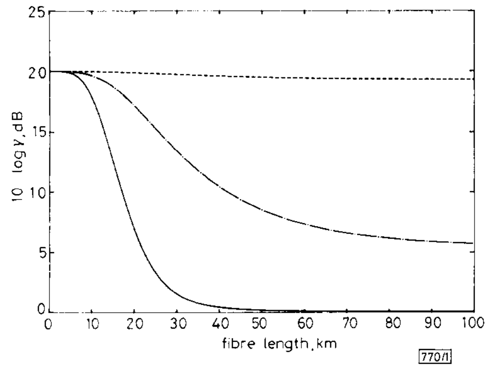

Fig. 1 *Variation of γ along fibre for various pump powers*

$S_{on} = 1$ mW
- - - - $P(0) = 0{\cdot}1$ W
—·—· $P(0) = 0{\cdot}3$ W
——— $P(0) = 0{\cdot}5$ W
System parameters are given as: $g_0 = 8 \times 10^{-14}$ m/W
$A = 2{\cdot}8 \times 10^{-11}$ m^2, $\alpha = 0{\cdot}2$ dB/km
$B_{eff} = 1{\cdot}1 \times 10^{11}$ Hz

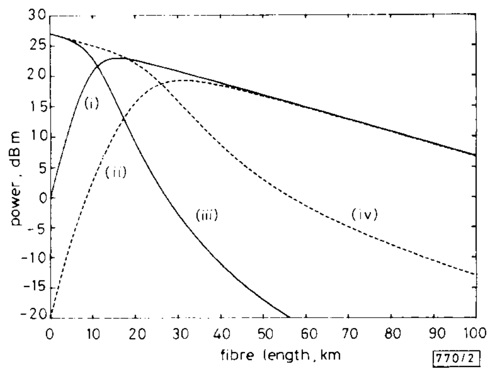

Fig. 2 *Signal and pump power variations along fibre with P(0) = 0·5 W, S_{on} = 1 mW, γ(0) = 20 dB*

(i) $S(z)$, with $S(0) = S_{on}$
(ii) $S(z)$, with $S(0) = S_{off}$
(iii) $P(z)$, with $S(0) = S_{on}$
(iv) $P(z)$, with $S(0) = S_{off}$

level so as not to cause significant pump depletion. However, the amplifier gain increases with pump power such that a high power pump is desirable to achieve high amplifier gain. Therefore a tradeoff exists between the extinction ratio and the amplifier gain. To ensure an acceptable γ at the far end the pump should be carefully chosen. Here we derive a simple rule to estimate the required pump power. From eqns. 5 and 6 we have

$$\xi + \eta = \left[\frac{v_p S(0)}{v_s P(0)} + \frac{hv_p B_{eff}}{P(0)}\right] \exp\left[K(1 - e^{-\alpha z})\right] \quad (9)$$

where ξ and η account for the amplified signal and the ASSP, respectively. By using the measured Raman gain profile[3] and assuming a 1 nm signal linewidth, B_{eff} can be calculated.[5] The term $hv_p B_{eff}$ at 1·5 μm is approximately given by

$$hv_p B_{eff} \simeq 10^{-8}\,\text{W} \quad (10)$$

For FRA used as a power amplifier, S_{on} and S_{off} are usually much larger than 10^{-8} W, hence

$$\zeta + \eta \simeq \frac{v_p S(0)}{v_s P(0)} \exp\,[K(1 - e^{-\alpha z})] = B \exp\,[K(1 - e^{-\alpha z})] \quad (11)$$

both in the ON and OFF states. Let

$$\gamma(0) = \frac{S_{on}}{S_{off}} \quad (12)$$

be the initial ON/OFF ratio and

$$B_{on,\,off} = \frac{v_p S_{on,\,off}}{v_s P(0)} \quad (13)$$

are the B values in the ON and OFF states. With the simplifications and eqn. 4, the extinction ratio at $z = L$ is given by

$$\gamma(L) = \frac{\gamma(0)\{1 + B_{off} \exp\,[K(1 - e^{-\alpha L})]\}}{1 + B_{on} \exp\,[K(1 - e^{-\alpha L})]} \quad (14)$$

If we allow 3 dB degradation, $\gamma(L) = \gamma(0)/2$, eqn. 14 becomes

$$B_{on} \exp\,[K(1 - e^{-\alpha L})]\left[1 - \frac{2}{\gamma(0)}\right] = 0 \quad (15)$$

which is the design rule to choose the pump power such that only 3 dB degradation is allowed.

The FRA can also be used as a repeater amplifier to boost weak signals. In this case the signal powers in the ON and OFF states are much smaller than those used in the transmitter power amplifier. Fig. 3 shows the relationship between extinction ratio and pump power for various $\gamma(0)$ with $S_{on} = 1\,\mu$W. When used in the repeater section, the role of ASSP becomes significant because of low signal level in the OFF state. The extinction ratio at the far end for $\gamma(0) = 30$ and 40 is nearly the same because in this case the ASSP could dominate the signal power in the OFF state. Compared with Fig. 1 the degradation is less if the same pump power is used because of the relatively low initial signal level. Again we see that serious degradation occurs when high pump power is used. Therefore the pump power should be kept at a level not to cause serious extinction ratio degradation.

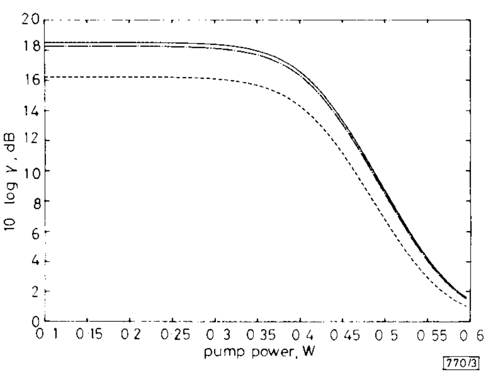

Fig. 3 *γ as function of pump power at z = 100 km*

---- $\gamma(0) = 20$ dB
—·— $\gamma(0) = 30$ dB
—— $\gamma(0) = 40$ dB

In conclusion we have studied the extinction ratio degradation caused by FRA. The application of FRA both as a transmitter power amplifier and a repeater amplifier are discussed. It is shown that FRA degrades the extinction ratio because of the amplified signal in the OFF state and the introduction of ASSP. The degradation increases with pump power and serious degradation occurs if high pump power is used. Because the amplifier gain increases with pump power, there exists a tradeoff between the achievable amplifier gain and the extinction ratio degradation. The design rule to determine the suitable pump power is presented.

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GaInAsSb/GaSb *pn* PHOTODIODES FOR DETECTION TO 2·4 μm

Indexing terms: Photodiodes, Diodes, Semiconductor devices and materials

$Ga_{0\cdot77}In_{0\cdot23}As_{0\cdot20}Sb_{0\cdot80}$/GaSb *pn* heterojunction photodiodes have been prepared by liquid phase epitaxy. They exhibit a long-wavelength threshold of 2·4 μm. The room-temperature dark current at $V = -0{\cdot}5$ V is 3 μA (10 mA/cm^2) and the external quantum efficiency is around 40% in the wavelength range 1·75–2·25 μm. The estimated detectivity D^* at 2·2 μm is $8{\cdot}8 \times 10^9$ cm Hz$^{1/2}$ W^{-1}.

The mid-infra-red wavelength domain (2–3 μm) is of great interest for spectroscopic studies, optical transmission through the atmosphere and lightwave communication systems using fluoride glass fibres. GaInAsSb photodiodes operating up to 2·3 μm have been prepared by liquid phase epitaxy (LPE),[1–5] as well as GaInAsSb/GaAlAsSb avalanche photodiodes with separate absorption and multiplication regions.[6] Devices based on the GaInAs ternary alloy, operating near 2·55 μm, have also been reported.[7,8] They are grown by the hydride vapour phase epitaxial technique on InP substrate using a compositionally graded $Ga_{1-x}In_xAs$ alloy to accommodate the high lattice mismatch (~2%) between the active zone and the substrate. The InAsSbP/InAs system, grown by LPE, was also used to realise photodiodes for detection in this mid-infra-red wavelength domain.[9]

We report on LPE grown GaInAsSb(*p*)/GaSb(*n*) heterojunction photodiodes showing a cutoff wavelength value of 2·4 μm.

Fig. 1 is a schematic cross-section of the diode. It consists of a Ge-doped p^+ GaSb window (~0·6 μm window) (~0·6 μm thick), an undoped *p*-$Ga_{0\cdot77}In_{0\cdot23}As_{0\cdot20}Sb_{0\cdot80}$ absorbing layer (~1 μm thick), and a Te-doped n^+-GaSb buffer layer (~5 μm thick), grown onto a Te-doped n^+-GaSb substrate (100) oriented. Conventional liquid phase epitaxy was used as the