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Erbium doped fibre lasers and amplifiers

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ABSTRACT

Recent advances in the field of Er^{3+}-doped optical fibre amplifiers and lasers operating around $\lambda=1.54\mu m$ will be described, with particular reference to 'new' pump wavelengths and practical pump sources for these devices.

1. INTRODUCTION

Er^{3+}-doped fibre amplifiers, which operate around $\lambda=1.54\mu m$ coinciding with the low-loss region of silica optical fibre, show great promise for use in future high-performance telecommunication systems [1,2]. In addition, Er^{3+}-doped fibre laser emission lies within the 'eye-safe' region of operation, and so high power versions of these lasers may find use in compact laser rangefinders.

The Er^{3+}-ion in glass forms a three-level system with one metastable level ($^4I_{13/2}$) emitting directly to the ground state in a broad emission band around $\lambda=1.54\mu m$, and tunable laser operation over most of this band is possible [3]. The Er^{3+}-ion also has an unusually long fluorescence lifetime ($\tau_f \approx 12ms$) and this makes the laser ideal for the generation of high peak power pulses using the technique of Q-switching [4]. This long lifetime also allows high gain to be achieved for low pump powers when the fibre is configured as an optical amplifier.

It is as an amplifier that the fibre has found most use. The combination of high saturation power, low noise, high immunity to pump noise and low power requirement combined with the ability to work at very high bit rates has made the Er^{3+}-doped fibre amplifier one of the leading contenders for use as a booster/repeater/pre-amplifier in high capacity telecommunication systems. Until recently, widespread acceptability of the Er^{3+}-doped fibre amplifier has been limited by the lack of availability of suitable pump sources. This is no longer a problem, and the performance of the amplifier using diode lasers as pump sources will now be discussed.

2. FIBRE AMPLIFIERS

2.1. Optical Pumping

To find widespread application, erbium-doped fibre amplifiers (EDFAs) must employ cheap solid-state pump sources. Several pump bands exist in erbium whereby it operates as a three-level system. These can be accessed using either frequency doubled diode laser pumped Nd:YAG lasers operating at 532nm [5,6] or diode lasers operating around 670nm [1,7,8], 807nm [9] and 980nm [5,10,11]. In addition erbium can be operated as a two level system by pumping directly into the metastable level with diodes operating around $1.49\mu m$ [12,13,14]. The merits of each pump wavelength will be discussed.

One might expect 807nm to be the preferred pump wavelength owing to the availability of high power diode lasers operating at this wavelength. Unfortunately, efficient pumping on this transition is severely impeded by excited-state absorption (ESA) of the pump light [15,16]. Pump ESA is a problem particular to 3-level end-pumped optical amplifiers and occurs when a further pump transition to a higher energy level is possible from the highly-populated metastable level responsible for the gain at $1.53\mu m$. The excited-state absorption transitions have the effect of depleting the pump light resulting in a reduction of pumping efficiency and hence gain. Typically, only 6dB of gain can be obtained for 15mW of pump light at 807nm [9].

The pump bands at 670nm and 532nm, although exhibiting reduced or minimal ESA, are also impeded by the large Stokes shift between pump and signal wavelengths with resulting reduced efficiency. Thus gain coefficients of 0.26dB/mW [7] and 1.35dB/mW [6] have been obtained for these two pump wavelengths respectively.

Both pump wavelengths, 980nm and 1.49μm benefit from a small Stokes shift between pump and signal wavelengths. This also allows the amplifier fibre to be single-mode at the pump wavelength allowing the pump dopant overlap to be maximised [10,17]. Both pump wavelengths are also free from ESA and thus give efficient performance. To date, gain coefficients of 3.9dB/mW and 2.1dB/mW have been demonstrated for 978nm diode laser [10] and 1.493μm F-centre laser [14] pumped EDFAs respectively.

Figure 1 shows the experimental set up for a 978nm diode laser pumped amplifier [10]. The output from the strained $In_{0.25}Ga_{0.75}As/AlGaAs$ quantum well diode pump laser [18] was launched into the wedge tipped fibre. The pump light was multiplexed with the signal light from a DFB laser operating at 1535nm via a dichroic coupler and launched into the amplifier fibre. Figure 2 shows the gain versus input signal for a launched power from the diode of 6.2mW. Higher diode pump powers are simulated using a dye-laser operating at 980nm. It can be seen that 24dB gain was obtained for only 6.2mW of pump, a gain coefficient of 3.9dB/mW. Further, the gain increased to in excess of 40dB for only 20mW of pump power.

Operation of erbium as a two-level system employing a 1.49μm pump wavelength relies on the Boltzmann thermal distribution of ions within the Stark split metastable and ground-states [12]. This can be represented as effective emission, $\sigma_e(\lambda)$ and absorption, $\sigma_a(\lambda)$ cross-sections for the two levels as shown in Figure 3 [19]. Since, at the short wavelength end ($\lambda < 1.5\mu m$) $\sigma_a > \sigma_e$, a population inversion can be obtained by pumping in this wavelength regime. However, since $\sigma_e(\lambda_p)$ is non-zero a complete inversion cannot be achieved and this results in a re-absorption at the signal wavelength and thus reduced efficiency. Figure 4 plots amplifier gain against pump wavelength for three pump powers of 21mW, 34mW and 54mW. In this case the amplifier was a germano-silicate erbium-doped fibre type, characterised by an NA of 0.21 and λ_{cutoff} at 1090nm. The optimum length was 15m. It can be seen from these results that for low pump powers there is an optimum pump wavelength, λ_p of approximately 1.48μm. Gain is reduced for longer pump wavelengths owing to increased $\sigma_e(\lambda)$ and at shorter pump wavelengths due to reduced $\sigma_a(\lambda)$. Increasing the pump power reduces the gain sensitivity to pump wavelength, the optimum being $\lambda_p \approx 1475$nm. In these experiments a maximum gain coefficient of approximately 1.1dB/mW was obtained.

2.2. Noise

The noise performance of any amplifier can be expressed by its noise figure (NF), the ratio of the signal to noise ratio at the input of the amplifier to that at the output. In the case of EDFAs, minimum NFs in the range 3.2 to 5.1dB have been predicted [20] and measured [21,22]. These values are extremely close to the 3dB quantum limit for the NF and along with its low insertion loss make the EDFA extremely attractive as a wideband optical amplifier.

In the case of a high gain EDFA, the dominant noise sources at the amplifier output are signal-spontaneous and spontaneous-spontaneous beat noise [23]. The NF for a single-mode EDFA with unpolarised output can therefore be expressed:

$$NF \simeq 10\log_{10}\left(\frac{4\mu GIh\nu(G-1) + 4(\mu h\nu(G-1))^2\Delta\nu}{2Ih\nu G^2}\right)$$

where I is the input signal, G the gain, h Plancks constant, ν and $\Delta\nu$ the optical frequency and bandwidth and μ is the effective amplifier inversion parameter at the amplifier input [20,24],

$$\mu = \frac{N_2\sigma_e(\lambda)}{N_2\sigma_e(\lambda) - N_1\sigma_a(\lambda)}$$

By either optical filtering ($\Delta\nu \approx 10GHz$) or ensuring large (>1μW) input signals to the amplifier, the first term in the NF equation dominates and the NF can be minimised to a value given by $10\log_{10}(2\mu)$.

The NF for an EDFA operated on a three-level transition has been shown theoretically to approach the quantum limit of 3dB [20]. This low NF is due to the high pump intensities which are obtained in the fibre, resulting in a near complete inversion. In this case $N_2 \gg N_1$ and $\mu \rightarrow 1$. Experimental measurements confirm this prediction [21,25].

Figure 5 shows NF measurements for a 980nm pumped amplifier as described in Section 1. It can be seen that with no optical filtering the NF is 2.9±0.7dB for input signals between -32dBm and -15dBm. With increasing input signal the NF decreases slightly owing to the amplifier saturation and thus reduced amplifier inversion, μ. For reduced input signal, the noise figure increases due to spontaneous-spontaneous beat noise, which could be reduced by optical filtering.

It is anticipated that pumping in band at $\lambda_p \approx 1.49\mu m$ will give a slightly increased NF owing to the non-zero emission cross-section, $\sigma_e(\lambda)$ at the pump wavelength. This limits the maximum population inversion which can be obtained to:

$$\frac{N_2}{N_1} = \frac{\sigma_a(\lambda_p)}{\sigma_e(\lambda_p)}$$

and thus increased NF. Giles et. al. [22] have demonstrated a NF of 4.8–5.1dB for a 1.49μm pumped EDFA. In addition, a NF < 5.3dB was measured over a 40nm signal bandwidth. Although 1.49μm pumping may result in a slightly higher NF than the 3-level pump wavelengths, the likely degradation is not of significant consequence for the majority of applications.

2.3. WDM/Gain Dynamics

Several authors have independently experimentally and theoretically investigated the gain dynamics and multichannel operation of EDFAs [26–29]. All show that as a consequence of the long fluorescence lifetime in an Er^{3+}-doped fibre amplifier, interchannel crosstalk and pump-noise breakthrough are minimal for modulation frequencies >100kHz.

Figure 6 shows a typical experimental set up for the measurement of crosstalk [26]. In this case, crosstalk was measured by modulating diode B with a 5MHz, 100% modulated sinusoidal signal whilst simultaneously modulating signal A at frequencies ranging from 10Hz to 20kHz. Since the population in the upper lasing level changes in step with the low-frequency modulation of laser A, the population inversion and hence gain seen by the signal from diode B is modulated. This mixes the signals and gives sidebands on the 5MHz signal. However, as the low-frequency modulation increases in frequency, the population inversion ceases to follow the modulation and a reduced gain modulation is seen. Two regimes of operation were considered: (a) signals A and B large (A=27μW, B=19μW), i.e. saturated operation, and (b) signals A and B small (A=20nW, B=18nW) i.e. small-signal operation. The ratio of upper sideband to fundamental power for these two conditions is plotted in Figure 7. The crosstalk is seen to roll off at high frequencies due to the slow change in the population inversion and, provided the signal contains no information at frequencies <100kHz, crosstalk will be suppressed by >40dB. This result also implies that the amplifier will be extremely linear and be suitable for use in subcarrier multiplexed video transmission systems operating in the megahertz frequency region [30].

2.4. Bandwidth

(a) Optical

Erbium exhibits several Stark split energy levels in its metastable and ground-states [31]. These give rise to a non-uniform gain spectrum which is dependent on the host glass [1,10,31,32]. In addition, the gain spectra is dependent on the populations of the metastable and ground-states and is thus also dependent on pump power [32] and pump wavelength [19]. Figure 8 shows the gain spectra for highly inverted silica/germania and silica/alumina erbium-doped glass. It can be seen that for the silica/germania fibre type the gain spectrum is peaky and centred at 1.535μm. Typically for a 30dB amplifier the 3dB bandwidth is ~ 3nm. The silica/alumina fibre type on the other hand has the (gain) peak shifted to 1.531μm and broadened to a 3dB bandwidth of 7nm for a 30dB amplifier. In addition, it is noted that there is a relatively constant gain region extending from approximately 1.538μmto 1.560μm, where gains in excess of 20dB have been demonstrated [33]. Furthermore, Atkins et. al. [19] have demonstrated that by pumping in-band at 1.49μm and by reducing the pump power to obtain a reduced amplifier inversion, a 25dB gain amplifier having a 3dB bandwidth of 35nm can be obtained.

(b) Electrical

Since the optical bandwidth is composed of several transitions it is anticipated that the electrical bandwidth will be smaller than the optical bandwidth. In addition, it is interesting to investigate if the frequency response is dependent on input signal level to the amplifier.

The AM and FM response of an EDFA has been characterised for signal modulation frequencies in the range 130MHz to 15GHz [34]. Both the amplifier gain and phase were found to be constant for both AM and FM modulated signals under both small-signal and saturated amplifier operation as can be seen from Figure 9. These results confirm the suitability of erbium-doped fibres for amplifying both amplitude and angle modulated signals for data rates in the range 10 to 20Gbit/s.

2.5. System Experiments

(a) Direct detection

The EDFA offers many advantages for high-speed direct-detection systems and has allowed transmission distances and bit rates to increase markedly. One of the best results to date employs twelve 1.48μm laser diode pumped EDFAs as both power and line-amplifiers [35]. These allowed transmission of 1.2Gbit/s data rates over 904km of fibre, a significant distance improvement over systems without EDFAs. The power penalty due to dispersion and the presence of the amplifiers was as small as 0.6dB at $10^{-}9$ BER, and an error floor due to accumulated noise was not observed, demonstrating the compatibility of Er^{3+}-doped fibre amplifiers with long-haul telecommunication systems.

(b) Multichannel and coherent systems

Multichannel coherent broadcast networks are of great interest for possible use in single-mode fibre subscriber systems. EDFAs have high potential for use in such networks because the number of end-users can be increased significantly.

Figure 10 shows an experimental set up to characterise an EDFA in a 16-channel coherent broadcast network experiment [33]. The transmitter lasers operated in the wavelength range 1538.8nm to 1540nm, where the amplifier provided a 22dB gain for the entire transmission experiment. Employing this set up the distribution of sixteen 155Mb/s signals to one of 256 end-users at a distance of 102km with 10^{-9} BER was obtained. This demonstrates a potential network capacity of $65Tbs^{-1}$.km.user and confirms that the EDFA will play a major role in the development of such networks.

3. FIBRE LASERS

Er^{3+}-doped fibre, in addition to its use as an optical amplifier, can be used as the gain element for a laser and provides a versatile and convenient source of radiation around 1.54μm. The high pump intensity attainable in a single-mode fibre in conjunction with the long fluorescence decay time of the Er^{3+}-ion in glass mean that it is easy to bleach the three-level erbium transition with milliwatt pump powers at diode laser wavelengths, thus making Er^{3+}-doped fibre lasers of practical interest. Of the many pump bands available, that near 800nm has been widely used due to the ready availability of GaAlAs diode lasers at this wavelength. Initial fibre laser output powers were less than 1mW [36], although 8mW output power has now been achieved using a high-power phased array as the pump source [37].

Attempts to improve the output power by co-doping the fibre with large amounts of ytterbium demonstrated that, while the output power remained the same, a greater range of pump wavelengths could be used [38]. However, in all of these experiments, the efficiency of the Er^{3+}-doped fibre laser has been limited by excited state absorption of the pump light. Fortunately, this problem can be avoided by pumping at a wavelength of 980nm. Recently, an Er^{3+}-doped fibre laser with a slope efficiency of 60% has been reported [39], corresponding to a quantum efficiency of almost unity (figure 11). The pump source used in this experiment was a Styryl 13 dye laser, although a Ti:sapphire laser could also be used in order to achieve high power operation and, with the advent of 980nm diode lasers, the realisation of a compact Er^{3+}-doped fibre laser becomes a possibility.

Another important attribute of the Er^{3+}-doped fibre laser is its ability to generate short, intense pulses using the technique of Q-switching. A compact, portable source of high peak power pulses at 1.54μm is expected to find many applications in optical time domain reflectometers, eye-safe laser rangefinders, fibre sensors, etc. The long fluorescence time constant of erbium in glass makes it highly efficient at storing energy and therefore ideal as a medium for a Q-switched laser.

An alternative method which may be used to generate even shorter pulses is that of mode-locking. It has recently been shown [40] that bandwidth limited pulses as short as 4ps at a repetition rate of 90MHz are obtainable by incorporating a lithium niobate guided wave modulator into the cavity of the Er^{3+}-doped fibre laser. By using a monolithic fibre geometry, it was possible to combine the elements of gain, self phase modulation and negative group velocity dispersion within the one device, leading to the concept of a stable, self-contained mode-locked system.

4. CONCLUSIONS

The Er^{3+}-doped fibre amplifier has been shown to be a promising contender for use as an optical booster in future telecommunication systems. The limitations which have been imposed by the need for a practical pump source have been largely overcome and, in a relatively short space of time, the amplifier has developed from being a laboratory experiment into a ruggedised, practical undersea system. Er^{3+}-doped fibre lasers will also find a niche in the marketplace as compact, efficient sources for telecommunications, fibre sensors and laser rangefinders.

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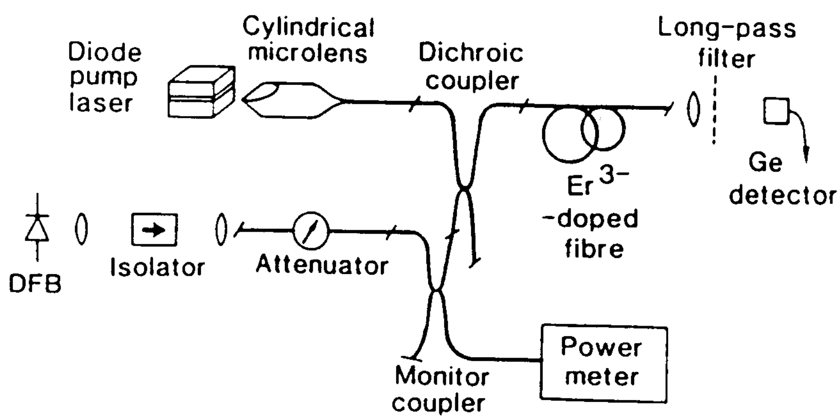

Figure 1 Experimental configuration of 978nm diode laser pumped erbium fibre laser

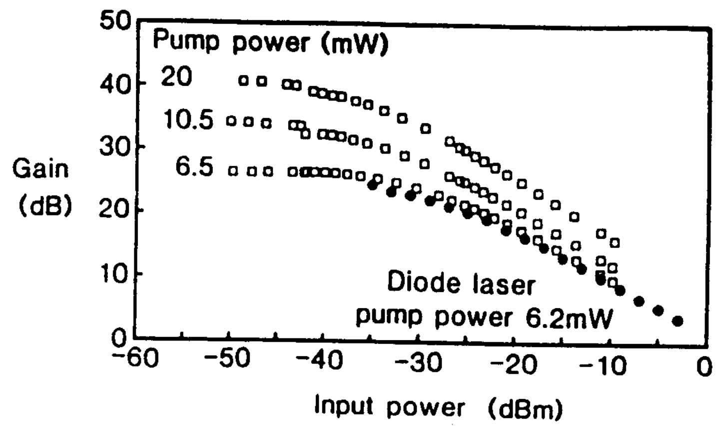

Figure 2 Gain vs input signal for diode pumped amplifier

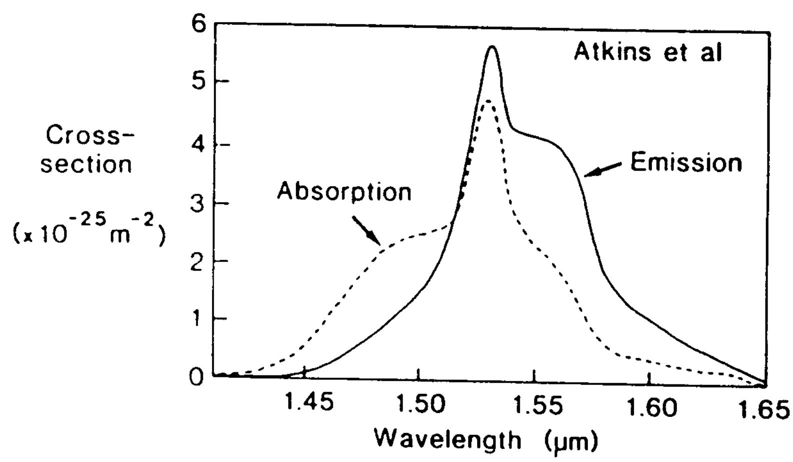

Figure 3 Emission and absorption cross-sections of erbium in alumino-silicate glass

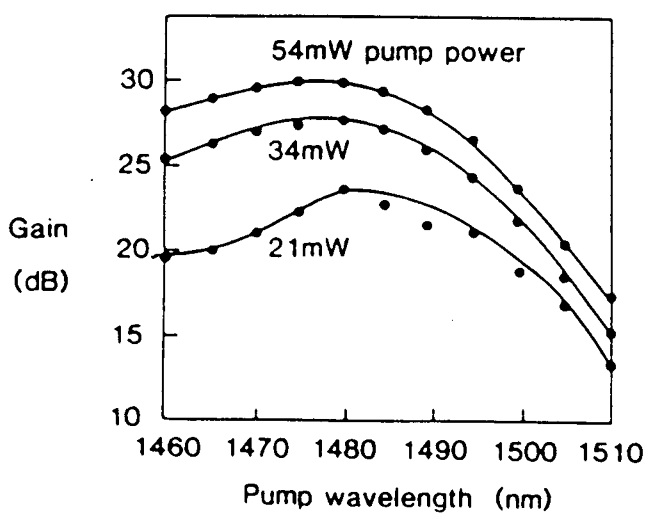

Figure 4 Gain vs pump wavelength for in-band pumping

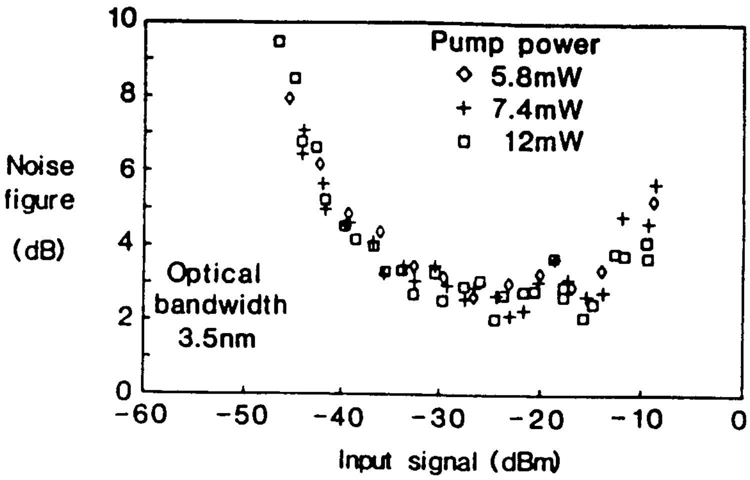

Figure 5 Noise figure of 980nm pumped fibre amplifier

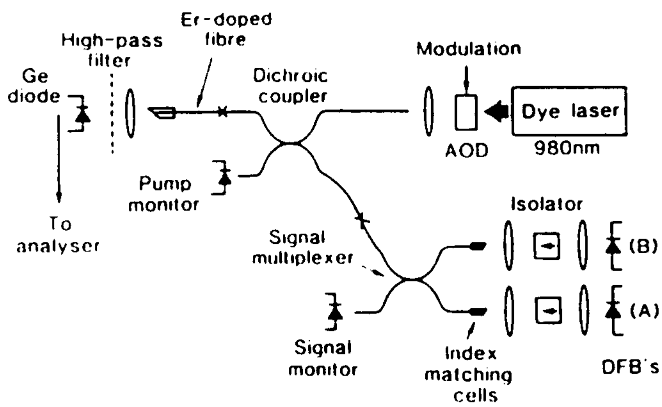

Figure 6 Experimental configuration for measuring crosstalk in fibre amplifier

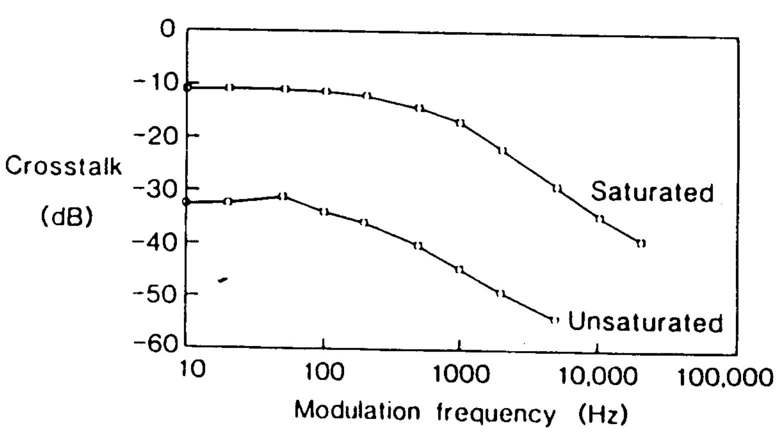

Figure 7 Dual wavelength crosstalk in fibre amplifier

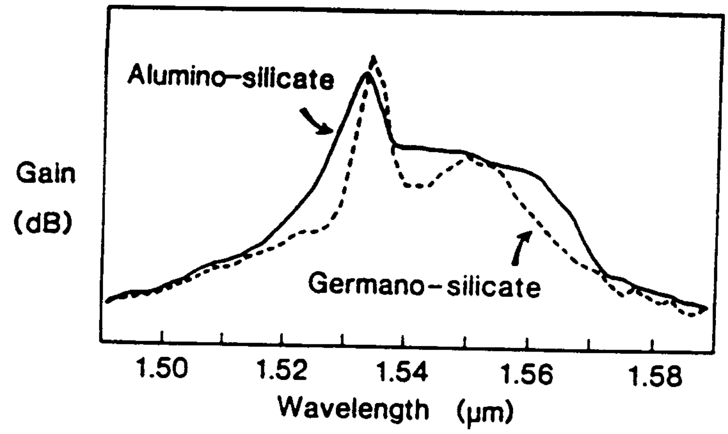

Figure 8 Gain spectra of alumino-silicate and germano-silicate glasses

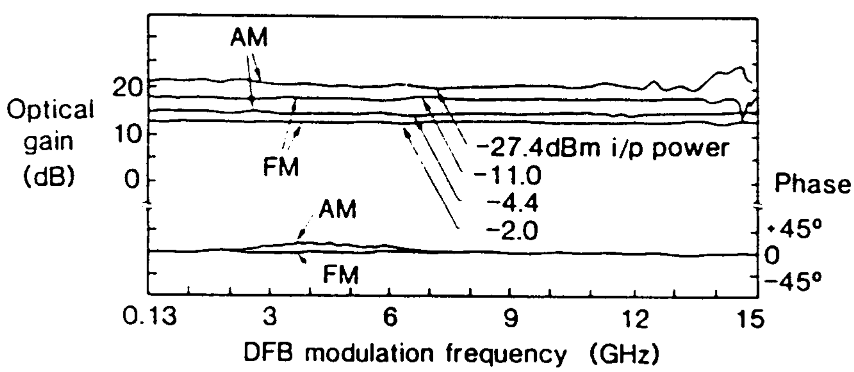

Figure 9 AM and FM response of fibre amplifier

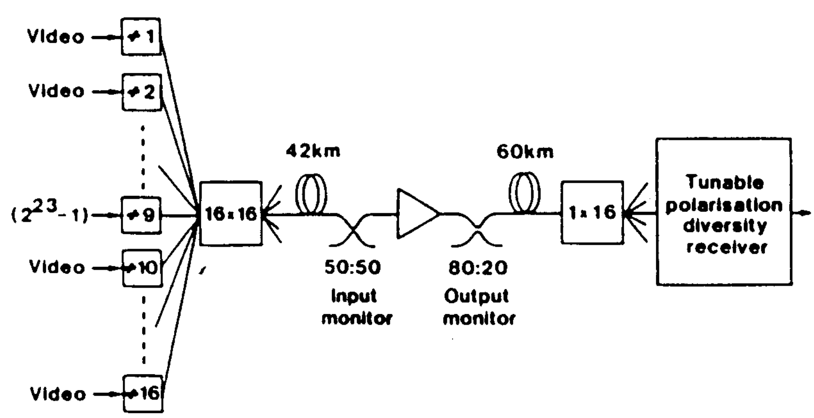

Figure 10 Experimental configuration of coherent broadcast network using fibre amplifier

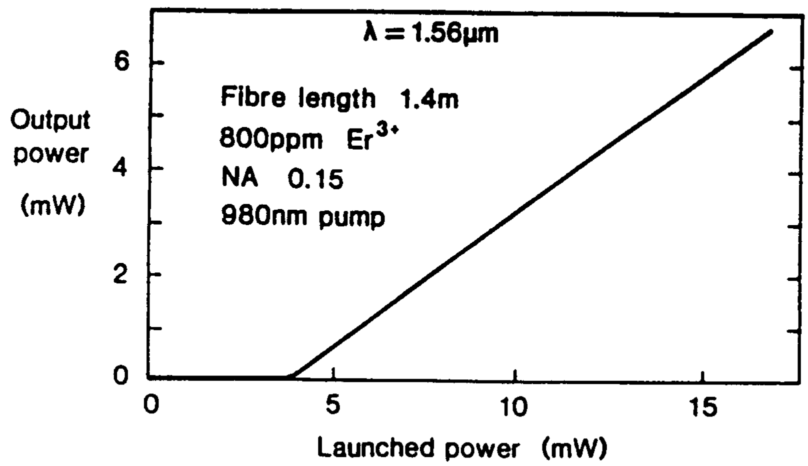

Figure 11 Lasing characteristic of erbium-doped fibre laser pumped at 980nm