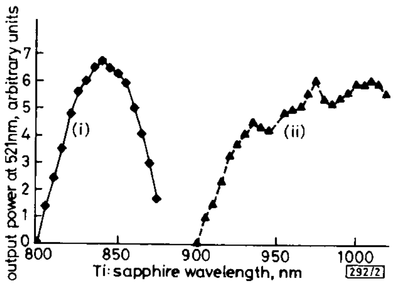

Fig. 2 *Output power at 521nm in 70cm fibre laser*

(i) Ti:sapphire laser power is 200mW, 985nm laser diode power is 80mW
(ii) Ti:sapphire laser power is 120mW, 833nm laser diode power is 120mW.
The Ti:sapphire laser is limited to operation below 1020nm

The broad acceptance bandwidth for the laser diodes indicated in Fig. 2 is of great practical importance. CW frequency up-conversion techniques that use second-harmonic generation require stabilised single-frequency laser diodes. Our up-conversion laser used high-power laser diodes that operated on several longitudinal modes, exhibited mode-hopping behaviour. The fibre laser placed a relatively low restriction on the absolute wavelengths of the pump sources. Only single spatial mode operation was a stringent requirement of the laser diodes. We observed no fluctuation in fibre laser output power due to laser diode mode-hopping behaviour.

In summary, we have demonstrated experimentally milliwatt-level visible laser powers from diode-pumped up-conversion fibre lasers. Clearly there is room for improvement. Fibre diameter, fibre length, cutoff wavelength and mirror reflectivities may be optimised for enhanced performance.

27 August 1993
Electronics Letters Online No: 19931203

D. Piehler and D. Craven (*Uniphase Corporation, 163 Baypointe Parkway, San Jose, CA 95134, USA*)

N. Kwong and H. Zarem (*Ortel Corporation, 2015 West Chestnut Street, Alhambra, CA 91803, USA*)

References

1 SMART, R.G., HANNA, D.C., TROPPER, A.C., DAVEY, S.T., CARTER, S.F., and SZEBESTA, D.: 'CW room temperature upconversion lasing at blue, green and red wavelengths in infrared-pumped Pr^{3+}-doped fluoride fibre', *Electron. Lett.*, 1991, **27**, pp. 1307–1309

2 ALLAIN, J.Y., MONERIE, M., and POIGNANT, H.: 'Room temperature cw tunable green upconversion holmium fibre laser', *Electron. Lett.*, 1990, **26**, pp. 261–262

3 GRUBBO, S.G., BENNETT, K.W., CANNON, R.S., and HUNTER, W.F.: 'CW room-temperature blue upconversion fibre laser', *Electron. Lett.*, 1992, **28**, pp. 1243–1244

4 WHITLEY, T.J., MILLAR, C.A., WYATT, R., BRIERLEY, M.C., and SZEBESTA, D.: 'Upconversion pumped green lasing in erbium doped fluoride fibre', *Electron. Lett.*, 1991, **27**, pp. 1785–1786

5 ALLAIN, J.Y., MONERIE, M., and POIGNANT, H.: 'Tunable CW lasing around 610, 635, 695, 885 and 910nm in praseodymium-doped fluorozirconate', *Electron. Lett.*, 1991, **27**, pp. 189–191

6 ALLAIN, J.Y., MONERIE, M., and POIGNANT, H.: 'Red upconversion Yb-sensitised Pr fluoride fibre laser pumped in 0.8μm region', *Electron. Lett.*, 1991, **27**, pp. 1156–1157

7 OSHISI, Y., KANAMONI, T., NISHI, T., TAKAHASHI, S., and SNITZER, E.: 'Gain characteristics of Pr^{3+} – Yb^{3+} codoped fluoride fiber for 1.3 μm amplifiers', *IEEE Photonics Technol. Lett.*, 1991, **3**, pp. 990–992

8 ZAREM, H., UNGAR, J., MITTELSTEIN, M., PASLASKI, J., and URY, I.: 'High-power single mode InGaAs lasers for pumping praseodymium-doped fiber amplifiers'. Conf. on Optical Fiber Communication, 1992, (Optical Society of America), Paper WL7

Nonlinear four-wave mixing in erbium-doped fibre amplifiers

B. Fischer, J.L. Zyskind, J.W. Sulhoff and D.J. DiGiovanni

Indexing terms: Fibre lasers, Multiwave mixing

Four-wave mixing in erbium-doped fibre amplifiers is presented and studied. Coupling in two cases is demonstrated: first, where one laser supplies all three input beams, and second, where two different lasers are used and the coupling is measured as a function of their relative detuning. This has potential uses in dynamic fibre-optic applications, such as filters and wavelength routing.

Erbium-doped fibre amplifiers (EDFAs) are active fibres exhibiting strong gain. Consequently, EDFAs can be used to generate nonlinearities and wave-mixing, which are much stronger than in passive fibre, thus permitting shorter fibre lengths and lower optical powers. Such nonlinear effects in EDFAs may have important applications. Recent studies reported strong two-wave mixing effects [1] and brought up the possibility of using such gratings as filters [2]. In two-wave mixing the two beams (1 and 2) which write the grating are the only inputs and the induced gain grating affects the writing beams themselves. Two-wave mixing in EDFAs has recently [1] been studied and observed. Reflection from the induced grating was detected by modulating one of the input beams and detecting the reflected power at the modulation frequency. As predicted by the coupled wave equations for two-wave mixing, at high modulation frequency (ν_{mod} > 20kHz) the effect of reflection from the grating is the sole contribution to the frequency modulated signal, and the reflected signal disappears when the the coherence of beams 1 and 2 is destroyed. At low modulation frequency the effect of temporal modulation of the gain saturation is added to the above grating reflection. The optical phase for both contributions is 180° with respect to that of the modulated input.

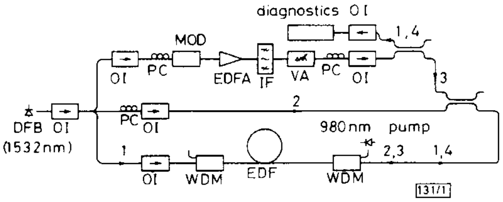

Fig. 1 *Experimental setup*

DFB represents a distirbuted feedback diode laser, OI is an optical isolator, PC is a polarisation controller, MOD is a $LiNbO_3$ modulator, IF is an interference filter, VA is a variable attenuator, WDM is a wavelength division multiplexer for 980nm and 1550nm, and EDF is an erbium-doped fibre under test

In four-wave mixing a third input, beam 3, with wavevector k_s close in magnitude to those of beams 1 and 2, generates a fourth beam, 4, by a reflection of beam 3 from the grating (see Fig. 1). Beam 3 may comprise, for example, several information-carrying channels at different wavelengths within the erbium gain spectrum. In this case the four-wave mixing process can be used to produce a reflected beam 4 consisting of one or perhaps a subset of these channels, with the channel selection dynamically tunable by changing the wavelength of beams 1 and 2.

Four-wave mixing can be understood by considering the coupled wave equation. We start with the nonlinear susceptibility which is taken to be [3–5] $\chi = \chi_0/1 + I/I_S$ where I is the local light intensity and I_S is the saturation intensity. This approximation is valid for $I << I_S$. The fields of the four beams are $E_i = A_i e^{i(k_i z - \omega_i t)}$, where $i = 1, 2, 3, 4$. Beams 1 and 2 are taken to be the grating writing beams. To simplify the wave mixing equations, we assume that $I_i << I_S$, where $I_i = |A_i|^2$ We also assume that $k_1 . k_2 = k_p$ and that beams 1 and 2 are mutually coherent. Then, we can write the coupled wave equations [1] for beams 3 and 4, neglecting the gratings set up by their mutual interaction and their interaction with beams 1 and 2:

$$\frac{dA_4}{dz} \simeq \tilde{g}A_4 + \kappa A_3^* e^{i2(k_p-k_s)} \qquad (1a)$$

$$\frac{dA_3}{dz} \simeq -\tilde{g}A_3 + \kappa A_4^* e^{i2(k_p-k_s)} \qquad (1b)$$

where [2] $\tilde{g} = g[1 - < I_1 + I_2 > / I_S]$, $g = k_{\chi 0}/2$, which in general is complex, but near the gain peak should be predominantly real, and the coupling term $\kappa = g < A_1 A_2^* > / I_S$ gives the reflection from the gratings induced by beams 1 and 2. The angled brackets [1] indicate the time average of the enclosed term over the characteristic response time of the gain dynamics, τ, which is of order 1–10 ms. For modulation frequency $V_{mod} << 1/\tau$ this average approaches the instantaneous value and experiences full modulation, while for $V_{mod} >> 1/\tau$ such terms have a constant value corresponding to averaging over the modulation. In the regime where beams 1 and 2 are much stronger than beams 3 and 4, κ, which is proportional to $A_1 A_2^*$, will be approximately constant over the length of the fibre. If we make the further approximation that all beams are of sufficiently low power that $\tilde{g}$ is also constant, then an analytical solution for the amplitude reflectivity r can be obtained [6–7]:

$$\begin{aligned} r &\equiv \frac{A_4(z=L)}{A_3(z=L)} \\ &= \frac{\kappa \sinh(SL)}{(\tilde{g} - i\Delta k)\sinh(SL) - S\cosh(SL)} \end{aligned} \qquad (2)$$

where $\Delta k = (k_s - k_p)$ is the wavenumber detuning from the grating induced by the pump beams 1 and 2 and $S^2 = |\kappa|^2 + (\tilde{g} - i\Delta k)^2$. Thus, we have a grating that has peak reflectivity for $k_s = k_p$ (Bragg condition) and, for real g, a bandwidth $\delta v = (c/2\pi n)\delta k$, where n is the refractive index and

$$\delta k = \left\{ (\frac{\pi}{L})^2 + \frac{|\kappa|^2}{1 + (\tilde{g}L/\pi)^2} \right\}^{\frac{1}{2}} \qquad (3)$$

(estimated by taking the first zeros of r). The grating can be generated either in an amplifier where the grating writing beams are provided externally as in the present experiment, or in an erbium-fibre laser where the intracavity beams of the laser itself provide beams 1 and 2 to write the grating.

Four-wave mixing is demonstrated using the setup in Fig. 1. The output of a 1532nm DFB laser was coupled into fibre and divided in three (see Fig. 1). The two grating-writing beams, denoted 1 and 2, were counterpropagated in 0.97m of erbium-doped fibre having an alumino-germano-silicate core with an erbium concentration of 2500*ppm*, a diameter of 2.5µm and a numerical aperture of 0.33. The powers of beams 1 and 2 were −4 dBm each, and the power of the 980nm pump beam was 40mW. The intensity of beam 3 was modulated on and off to distinguish the reflected beam from the transmitted beam 1. The modulation frequency was varied from 100Hz to 20MHz to distinguish between temporal modulation of the gain saturation and reflections from the induced grating. To destroy its coherence with beams 1 and 2, beam 3 was passed through a 4.86km length of singlemode fibre before being coupled into the EDFA.

The grating reflection can be distinguished from other effects, such as spurious reflections and temporal modulation of the gain arising from the modulation of beam 3, by cutting off beam 2 to destroy the grating. The difference between the signal detected when all three beams are present and that when $I_2 = 0$ is positive only for high modulation frequency ($v_{mod} > 100$kHz) where grating reflection dominates the residual effects of temporal modulation of the saturation. In this region the detected intensity corresponds to a power reflectivity of $R = |r^2| = 6\%$ for high v_{mod}, as determined by comparison to the Fresnel reflection from the polished end of a fibre.

In a second configuration two separate lasers were used to supply the input beams in order to measure the bandwidth of the grating. The 1532nm DFB laser was used as the source for the grating writing beams 1 and 2 and an external cavity diode laser supplied beam 3, i.e. provided the input for leg 3 in Fig. 1. The detuning was measured using a Fabry–Perot etalon with a finesse of 2500 and a free spectral range of 15GHz. Using the slow drift in the detuning before the lasers were completely stabilised, we were able to map the reflection band (Fig. 2). When ω_3 differed from $\omega_1 = \omega_2$ by more than a few hundred megahertz, the signal was less than 1µV. The measured bandwidth for this grating is ~110MHz. This is in good agreement with the estimate provided by eqn. 3 for the parameters of the present experiment, i.e. $L = 0.97$m, $1\text{m}^{-1} < \tilde{g} < 4\ \text{m}^{-1}$ and $0.1\text{m}^{-1} < \kappa < 0.5\text{m}^{-1}$ gives Δv . ($10^8/L$) Hz = 103MHz. For most practical parameters, Eqn. 3 will be dominated by the first term, so to increase the bandwidth to meet the needs of high-speed digital communications it will be necessary to use proportionately shorter fibres. To obtain adequate reflectivity this will require in turn higher erbium concentration. Estimation of the reflectivity is less straightforward because of the strong dependence on all the parameters as well as on the simplifying assumptions made in the analysis leading to eqns. 1–3.

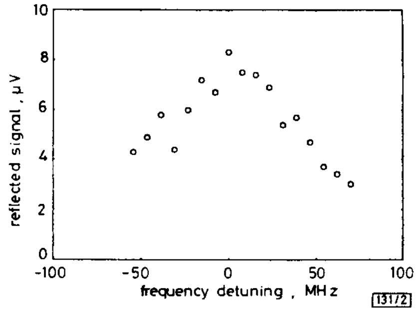

Fig. 2 *Reflected signal as function of frequency difference between signal beam and grating writing beams*

Dynamic wave mixing and the resulting induced gratings may be used as controllable filters, the parameters of which can be changed in real time, for applications such as wavelength division multiplexing and wavelength routing. The Bragg wavelength of the grating can be changed by changing the wavelength of the grating k_p. The bandwidth can be controlled by the choice of fibre length, and, to some extent, through κ by adjusting the intensity of beams 1 and 2 (which induce the gratings), the intensity of the gain pumping beam (here with a wavelength of 980nm) or the fibre doping level.

13 August 1993

Electronics Letters Online No: 19931161

B. Fischer (*Department of Electrical Engineering, Advanced Optoelectronics Research Center, Technion – Israel Institute of Technology, Haifa 32000, Israel*)

J. L. Zyskind and J. W. Sulhoff (*AT&T Bell Laboratories, Crawford Hill Laboratory, 791 Holmdel-Keyport Rd., Holmdel, NJ 07733, USA*)

D. J. DiGiovanni (*AT&T Bell Laboratories, Murray Hill Laboratory, 600 Mountain Ave., Murray Hill, NJ 07974, USA*)

References

1 FISCHER, B., ZYSKIND, J.L., SULHOFF, J.W., and DIGIOVANNI, D.J.: 'Nonlinear wave-mixing and induced gratings in erbium-doped fiber amplifiers', *submitted to Opt. Lett.*

2 FRISKEN, S.J.: 'Transient Bragg reflection in erbium-doped fiber amplifiers', *Opt. Lett.*, 1992, **17**, p. 1776

3 SOAN, R.J., CASE, A.D., and HUTCHINSON, R.H.: 'High-reflectivity four-wave mixing by saturable gain in Rhodamine 6-G dye', *Opt. Lett.*, 1992, **17**, pp. 781–783

4 TIMOTIJEVIC, D., BELIC, M., and BOYD, R.: 'Two and four wave mixing with saturable absorption and gain', *IEEE J. Quantum Electron.*, 1992, **QE-28**, p. 1915

5 DESURVIRE, E.: 'Study of the complex atomic susceptibility of erbium-doped fiber amplifiers', *J. Lightwave Technol.*, **LT-8**, p. 1517

6 LAM, D.K.W., and GARSIDE, B.K.: 'Characterization of single-mode fiber filters', *Appl. Opt.*, 1981, **20**, p. 440

7 YARIV, A.: 'Optical electronics' 4th Edn. (Saunders College Publishing, 1991), p. 502