Tuesday **MORNING**
22 May 1990 **JTUA**
SANTA ANA ROOM A9

8:00 AM Joint Symposium on Doped Fiber Lasers

Gary Bjorklund, *IBM Almaden Research Center, Presider*

8:00 AM Invited paper

JTUA1 Recent developments in optical fiber lasers

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A wide range of developments are reviewed including reports on progress aimed at high power operation, short pulse operation, and upconversion lasing.

8:30 AM

JTUA2 Diode laser pumped 2.8-μm fluorozirconate fiber laser

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We report the first observation of cw lasing at 2.78 μm in an erbium doped fluorozirconate (ZBLAN) single-mode host fiber, pumped by a laser diode array emitting at 792 nm. An erbium doped fluorozirconate single-mode cw fiber laser at 2.71 μm pumped by a tunable argon laser at 476.5 and 501.7 nm was recently reported by Allain *et al.*[1] Brierley and France[2] earlier reported a cw laser at 2.7 μm, also pumped by a tunable argon laser, in an erbium doped multimode fiber. Excited state absorption (ESA) of the pump beam by the terminal laser level population was the proposed mechanism for overcoming unfavorable branching ratios and also allowing cw lasing on a normally self-terminating transition.[3] In contrast to the argon laser, diode pumping has the advantages of much higher efficiency and compactness. A further advantage afforded by the glass host is the inhomogeneously broadened absorption level allowing for flexibility in the selection of a laser diode pump. In operation, the laser diode pumps the $^4I_{9/2}$ level (see Fig. 1). The decay of the $^4I_{9/2}$ into the $^4I_{11/2}$ has an efficiency of nearly 100%: Quimby and Miniscalco[3] have shown that cw lasing may be possible pumping into the $^4I_{9/2}$ level in the ZBLAN host without the necessity of ESA or energy transfer taking place. Our results are in general agreement with this conclusion.

The laser was constructed by butt coupling a 50-cm length of 0.5% ErF_3 doped fiber between flat 2.8-μm laser mirrors appropriately coated. The core diameter was nominally 13 μm giving a cutoff wavelength at 2.2 μm for single-mode operation. The diode pump has been described previously.[4]

The output wavelength was dependent on pump power in a manner similar to that described by Auzel *et al.*[5] in a bulk glass sample. With an 80% output coupler and at pump powers near threshold, the laser output was at 2.71 μm, whereas at the highest powers the laser operated at 2.78 μm. The laser performance for different values of output coupling is shown in Fig. 2. The relatively small change in lasing threshold for different values of output coupling is mainly due to internal cavity losses. We estimate these losses to be ~10–20% single pass based on lasing threshold as a function of mirror reflectivity. Mirror losses, H_2O absorption, imperfections, self-saturation, upconversion, and ESA from the $^4I_{11/2}$ are possible loss mechanisms. An increase in threshold from 4 to 9 mW was measured when going from a 50-cm fiber length to a 120-cm fiber length, indicating that the main loss mechanism is due to the fiber. A threshold of 4 mW with a 95% output coupler and slope efficiency of 3% with an 80% output coupler was measured for a 50-cm fiber. For a 20-cm fiber the threshold was 1.2 mW, and a slope efficiency of 12% was measured. The relatively small slope efficiency observed is a result of internal fiber and coupling losses, a photon decrement of 0.28, a low quantum efficiency of the $^4I_{11/2}\rightarrow{}^4I_{13/2}$ transition, and a long lower level lifetime.

1. J. Y. Allain, M. Monerie, and H. Poignant, Electron. Lett. **25,** 28 (1989).
2. M. C. Brierley and P. W. France, Electron. Lett. **24,** 15 (1988).
3. R. S. Quimby and W. J. Miniscalco, Appl. Opt. **28,** 14 (1989).
4. R. Allen and L. Esterowitz, Appl. Phys. Lett. **55,** 721 (1989).
5. F. Auzel, D. Meichenin, and H. Poignant, Electron. Lett. **24,** 1464 (1988).

8:45 AM

JTUA3 Absorption-emission cross-section ratio for Er^{3+} doped fibers at 1.5 μm

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Erbium doped optical fibers have been demonstrated to be both efficient and practical optical amplifiers in the 1.5-μm region.[1] Research is now concentrated on optimizing the performance of such amplifiers. Accurate modeling allows possible routes to optimization to be readily evaluated. The ratio of absorption cross section σ_A to that for emission σ_E, both at the gain peak and across the band, is crucial to such a model, particularly for in-band (e.g., 1490-nm) pumping.

Several determinations of the absorption emission cross sections have been made for the $^4I_{13/2}\leftrightarrow{}^4I_{15/2}$ transition of Er^{3+}.[2-4] All report that at the gain peak the ratio σ_A:σ_E is less than one, values typically being 0.8. Initial experiments on fiber optimization for amplifiers[1] showed us that the magnitude of the gain never exceeded that of the ground state absorption, even in conditions of very strong pumping. This brings into question the quoted values for the cross-section ratio. Specific experiments were undertaken to examine this in more detail.

The loss of a length l of fiber is given by $\eta Nl\sigma_A$, where N is the number of ions per unit volume in the fiber and η is the transverse overlap between the dopant and optical field. Under high pumping at 980 nm the gain asymptotically approaches $\eta Nl\sigma_E$. The ratio of gain and loss for a given fiber length thus provides a measure of the ratio σ_A:σ_E. Such measurements were performed at the gain peak on several fibers, and an example is shown in Fig. 1. The ratio σ_A:σ_E is found to be (1.2 ± 0.1):1 and applies to both GeO_2 silica and Al_2O_3 silica fiber types.

Previous estimates of σ_A and σ_E have been based on the Fuchtbauer-Ladenburg (FL) equation in which the cross sections are evaluated from the shape of the absorption and emission spectra, the radiative lifetime of the upper level, and the manifold degeneracies. This analysis was conducted on our fibers, and σ_A:σ_E was found (at the gain peak) to be ~0.8:1, in broad agreement with previous reports. Thus there is a discrepancy between the gain–loss and spectroscopic techniques. The FL equation approach involves several assumptions, one of which is that the process of absorption follows the same path as that of emission: we believe this to be a false assumption in the present case. In reality emission involves transitions predominantly from the lower Stark levels of the upper manifold ($^4I_{13/2}$) to all levels of the ground state manifold. Absorption, on the other hand, is dominated by transitions from the lower Stark levels of the ground state manifold to all those of the upper state.

The two processes would still be equivalent if the probability of transition between any two Stark levels was the same. Recent fluorescent line narrowing work suggests that such probabilities are not equal.[5] As a result the assumptions of the FL equation are inappropriate for the analysis of the erbium system. The gain loss technique reported here thus provides a more reliable measure of the cross-section ratio and will be useful in modeling the erbium amplifier. Further data on the spectral variation of the cross-section ratio are also presented.

1. For example, R. S. Vodhanel *et al.*, Electron. Lett. **25,** 1386 (1989).
2. W. J. Miniscalco, L. J. Andrews, B. A. Thompson, T. Wei, and B. T. Hall, in *Technical Digest, Topical Meeting on Tunable Solid State Lasers* (Optical Society of America, Washington, DC, 1989).
3. E. Desurvire and J. R. Simpson, IEEE/OSA J. Lightwave Technol. **LT-7,** 835 (1989).
4. C. G. Atkins, J. F. Massicott, J. R. Armitage, R. Wyatt, B. J. Ainslie, and S. P. Craig-Ryan, Electron. Lett. **25,** 910 (1989).
5. S. Zemon, G. Lambert, W. J. Miniscalco, L. J. Andrews, and B. T. Hall. Proc. Soc. Photo-Opt. Instrum. Eng. **1171,** paper 23 (1989).

9:00 AM

JTUA4 Limits on output power in a fiber amplifier

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The signal output power in a fiber amplifier has been limited to date by the available pump power.[1,2] We consider here the limits on signal output power when arbitrarily large pump power is available.

The transition rates relevant for the discussion are indicated in Fig. 1 for a three-