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Efficient upconversion laser action in Tm^{3+} and Pr^{3+}-doped ZBLAN fibers

P. R. Barber, H. M. Pask, C. J. Mackechnie,
D. C. Hanna, A. C. Tropper,
R. D. T. Lauder, S. T. Davey,*
D. Szebesta,* *Optoelectronics Research Centre and Department of Physics, University of Southampton, Southampton SO9, 5NH, U.K.*

Visible wavelength lasers are much sought after for many applications. In this paper we report that significant powers at blue (46 mW), green (5 mW) and red (30 mW) are now available from Tm^{3+} and Pr^{3+}-doped ZBLAN fiber lasers using very convenient pumping schemes based on the Yb^{3+}-doped silica fiber laser.

Ytterbium-doped silica fiber lasers are extremely versatile sources[1] and can be pumped with a wide range of wavelengths including 840 nm and 974 nm (available from diode lasers) and 1047 nm and 1064 nm (from Nd^{3+} doped crystals). With the use of photorefractive fiber gratings, high conversion efficiencies (up to 84%) can be obtained at any wavelength from 1.0 to 1.2 μm. These characteristics make an Yb^{3+}-doped silica fiber laser ideal for efficient pumping either the Tm^{3+} or Pr^{3+} upconversion lasers.

Laser output in the blue spectral region has been produced by three step upconversion of infrared light in the 1100- to 1180-nm region in Tm:ZBLAN fiber.[2] The Yb^{3+}: silica fiber was pumped at 1047 or 1064 nm and fiber gratings were used to provide output at 1100, 1112, 1128 or 1141 nm. The 100-ppm Tm^{3+}-doped ZBLAN fiber from Le Verre Fluoré had an NA of 0.21 and a cutoff wavelength of 800 nm. Blue laser results have been obtained with each of these pump wavelengths. As predicted by blue fluorescence measurements made with an OPO, pumping at 1141 nm produced the lowest threshold result. This was 11.3 mW of launched power in a cavity formed by two high reflecting mirrors butted on to 0.6 m of fiber. Slope efficiencies of up to 20% have been obtained giving 46 mW of blue output in a single spatial mode from a cavity consisting of one high reflecting mirror and a 37% transmitting output coupler.

In the case of the Pr^{3+}-doped ZBLAN laser, the Yb^{3+}-doped silica laser was pumped at 840 nm with the output of a TiS laser. Fiber gratings were spliced to each end of a 6 m length of fiber to enforce oscillation at 1020 nm. This length of fiber was chosen so that roughly equal amounts of the two pump wavelengths required for the upconversion process[3] (lasing at 1020 nm and unabsorbed pump at 840 nm) were obtained.

The Pr^{3+}-doped fiber used in this work was fabricated at British Telecom and had a measured concentration of 480 ppm by weight. The fiber diameter was 3.25 μm, and the numerical aperture was ~0.2. Laser output at 493, 520 and 635 mm has been investigated and the results obtained to date are summarised in Table 1, where the thresholds and slope efficiencies are in terms of power incident on the launch objective.

CMK6 Table 1. Summary of Pr^{3+}:ZBLAN Laser Results Where R1 and R2 Are the Mirror Reflectivities at the Launch and Output End Respectively

Laser Wavelength	Length (m)	R1	R2	Threshold (mW)	Slope Efficiency	Output Power (mW) (1 W TiS incident)
635 nm	5.7	100%	73%	25	11%	34
520 nm	2.5	98%	93%	170	3%	5
493 nm	2.5	99%	95%	240	3%	3

In conclusion, it has been shown that the Yb^{3+}-doped silica laser which in principle can be diode pumped provides a convenient and efficient means of obtaining the pump wavelengths required for upconversion in both Tm^{3+} and Pr^{3+} ZBLAN fiber, from which significant powers at 480, 493, 520 and 635 nm can be achieved.

* *British Telecom Research Laboratories, Martlesham Heath, Ipswich, IP5 7RE, U.K.*

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Effect of output coupling on single-polarization fiber lasers

D. G. Cooper, J. L. Dexter, R. D. Esman, *U.S. Naval Research Laboratory, Optical Techniques Branch, Code 5672, Washington, DC 20375-5338*

Single-polarization fiber lasers (SPFLs) are needed for numerous polarization-sensitive applications, including external modulation, fiber optic gyros, and interferometric sensors. Highly birefringent[1] and single-polarization Er-doped fiber amplifiers (EDFAs) have been demonstrated; however, both designs require rather exotic non-commercial fiber which is difficult to fabricate and expensive. Here we present several high-efficiency SPFL configurations that can utilize dual-polarization fiber with gain; the design is independent of both inherent and varying birefringence. The importance of output coupling ratio to output power, signal to amplified spontaneous emission (SNR), and tuning range is examined.

The basic amplifier configuration (Fig. 1(a)) consists of a standard EDFA and a 45° Faraday rotator and mirror combination (FRM). Polarized light, e.g. from a polarization beam splitter (PBS) or polarization-maintaining fiber (PMF), is injected into the non-PMF EDFA. After filtering, the light is then reflected from a FRM for a second pass through the filter and EDFA. The FRM reflects the light into its orthogonal polarization state. On retracing the fiber the light is everywhere orthogonal to the first-pass radiation and therefore avoids spatial hole burning and polarization-mode competition[1] while being polarized on the opposite axis upon output. Laser cavities can be completed by (1) utilizing a PBS, an isolator, and output coupler, and associated lengths of PMF (Fig. 1(a)),[2] utilizing an output coupler, a second 45° Faraday rotator, a polarizer (P), and a mirror (Fig. 1(b)), or (3) utilizing a Faraday rotator, a polarizer, and a partial mirror as the output coupler (Fig. 1(c)) to PMF. There are several consequences of these designs that are particularly advantageous: the double-pass configuration allows higher gain and efficiency, the counter propagating light is in an orthogonal polarization state at each point in the fiber so that (a) there is no spatial hole burning and (b) (reciprocal) birefringence is compensated.[3] The laser operates in all ways like previously published tunable fiber lasers, but with the added advantage of being linearly polarized and environmentally stable. The 3-dB tuning width is found to be 1558 ± 28 nm.

A study of the performance characteristics of the laser cavities shown in Fig. 1 was achieved by using a variable PM coupler (VPMC).[4] This VPMC is a polished type coupler where the coupling ratio is varied by transversely sliding the two halves of the polished coupler with respect to each other. The coupling ratio versus the transverse fiber offset of the VPMC is plotted in Fig. 2(a) and corresponds to the ratio of the light coupled out of the laser cavity. The coupling ratio increases as the fibers approach each other and then drops to a local minimum surrounding zero fiber offset. This local minimum results from the fibers interaction length being greater than the coupling length.[5]

The power output and signal to noise ratio (SNR) of the laser cavity shown in Fig. 1(b) is plotted in Fig. 2(b). It clearly shows that the lasers output increases as the output coupling ratio increases. A maximum output power of 4.6 mW (limited by the EDFA saturated output power) and a SNR of ~40 dB, is attained with a output coupling ratio of 85% at 1550 nm. At coupling ratios greater than this the output laser power and SNR are both seen to drop sharply. The power measured at 100% output coupling was attributed to ASE generated by the EDFA. An asymmetry is seen in the lasers SNR with respect to which