EFFICIENT SUPERFLUORESCENT EMISSION AT 974 nm AND 1040 nm FROM AN Yb-DOPED FIBER

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End-pumping of an Yb-doped single-mode fiber has yielded > 10 mW and 30 mW of broadband superfluorescence at 974 nm and 1040 nm, respectively. Slope efficiencies > 40% have been obtained. Pump wavelength dependent linewidths between 2 nm and 19 nm have been observed.

1. Introduction

Fiber lasers and amplifiers have received increasing attention in recent years because of their many attractive features. These include low pump thresholds, high slope efficiencies, wide tunability and lasing at new wavelengths. Recently it has also been pointed out [1] that they can make efficient superfluorescent sources, for which there are applications in sensor devices such as fiber-optic gyroscopes. Superfluorescent or ASE (amplified spontaneous emission) lasers, according to the terminology of Siegman [2], are based on the principle that if the gain of a medium is high enough, ASE can grow to a significant fraction of the saturation intensity in a single pass through the gain medium. Rare-earth doped single-mode fibers offer particular promise as superfluorescent sources in that gains achievable are typically of the order of 1 dB per milliwatt of absorbed power. With a gain requirement of typically 30–40 dB for superfluorescent emission (or 15—10 dB per pass for a double pass configuration), this places the pump power requirement within reach of diode lasers. A further advantage of the fiber geometry is that its output can be efficiently and conveniently injected into other fibers. This is not the case for commercially available sources, such as superluminescent diode lasers.

The only previous experimental reports [3,4] on a superfluorescent fiber laser (SFL) described a Nd-doped fiber pumped with 140 mW of light from a dye laser. The SFL emitted 10 mW in a 17 nm wide band centered at 1080 nm. The high slope efficiency (40%) of this device demonstrates the potential usefulness of SFL's as wavelength shifters.

In this letter we report on a highly efficient SFL based on an Yb-doped single-mode fiber. Emission can be chosen to occur either at 974 nm or near 1040 nm. The 974 nm emission is of particular interest for two reasons. It demonstrates that practical SFL's are not restricted to operate on four-level transitions, despite the fact that for a three-level transition the ground state population must be significantly depleted in order to prevent reabsorption of the emitted light. Of further significance is that this SFL provides an efficient source of light at 974 nm. This wavelength region has recently been identified [5] as the optimal one for pumping erbium-doped lasers and amplifiers.

2. Background

We have described the behavior of Yb-doped fiber lasers elsewhere [6,7]. To summarize, Yb^{3+} has the energy level structure shown in fig. 1. The ground state $^2F_{7/2}$ has, in principle, up to four Stark components. The positions of three of these (a, b and c) have been determined from room temperature emis-

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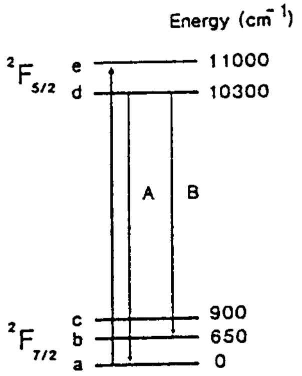

Fig. 1. Energy level diagram for Yb^{3+} in silica.

sion spectra. The configuration of Yb^{3+} has only the ^2F term, so that $^2F_{5/2}$ is the only excited manifold of relevance. Other excited states have much higher (UV) energies since they correspond to a different configuration. Two of the Stark levels (d, and e) of this manifold are resolved in absorption with peaks centered at 910 nm and 974 nm. Pumping into level e leads to a fast non-radiative decay into level d, whose fluorescence lifetime we have measured to be $\tau=0.77$ ms. Laser action has been observed from this level to the ground state multiplet. The population of level b at room temperature is approximately 4% of the total ground state population, making transition B (d→b) close to four-level in nature. Continuously tunable laser action on this transition and d→c from 1010–1162 nm has previously been demonstrated [7]. Laser action at 974 nm from d to a (transition A) has also been demonstrated [8,9]. This transition is purely 3-level in nature.

We have not attempted any detailed numerical modelling of the behavior of this superfluorescent emission as such a model would need to include a number of complicating features. These include the double-pass geometry, the fact that there may, in general, be three intense fields present (pump and emission at both 974 nm and 1040 nm) with the pump being heavily depleted along the fiber length, and the fact that the ground state population of the Yb^{3+} is heavily depleted by the pump. These features may in principle be modelled along lines which are essentially an extension of the treatment in ref. [1]. However, a further feature which we have observed, that the emission wavelength and linewidth can depend on the pump wavelength, indicates that a rate equation approach with a simple model of the Yb^{3+} levels, will not give a complete picture. We can nevertheless understand the overall qualitative behavior as follows.

The principal quantities that determine the SFL behavior and which can be varied are the fiber length L (or more generally the product of the fiber length and the dopant concentration), the pump power P_p launched into the fiber and the pump absorption cross-section, which depends on the choice of pump wavelength. Other quantities play an important role, but cannot be varied. These include the emission cross-sections σ_{da} and σ_{db} (and in particular their ratio σ_{da}/σ_{db}), and the fiber numerical aperture and core size. The last two parameters determine the degree to which the pump and emission fields overlap in the fiber.

In order to achieve inversion on transition A it is necessary to pump half the ground state population into level d. This requires a pump intensity at least equal to the saturation intensity given by $I_{sat}=h\nu_{pump}/\sigma_{ae}\tau$, where σ_{ae} is the absorption cross-section on the a→e transition, and τ is the fluorescence lifetime of level d. Let $p(r)$ and $s(r)$ be the normalized radial intensity distributions of the pump and signal, respectively. The effective area of the fiber core is then [10] $A_{eff}^{-1}=\iint p(r)\,s(r)\,d^2r$, where the integral is over the core area. Transition A will then be inverted at the front end (i.e. the pump input end) of the fiber if a power $P_{sat}=I_{sat}A_{eff}$ is launched ($\simeq 2$ mW for the fiber used here, at $\lambda_p=900$ nm). The available powers were in fact considerably higher than this. This allows us to strongly bleach the fiber, i.e. leave only a very small population in the ground state, over fiber lengths which were many times the small-signal pump-extinction length. As a result of this strong bleaching, light emitted on transition A is only weakly reabsorbed as it propagates through the fiber. We find from the emission spectrum that $\sigma_{da}/\sigma_{db}\simeq 4$ at linecenter. The 974 nm emission is therefore favored and if the fiber is strongly inverted with respect to both levels a and b, the gain at 974 nm will be higher than that at 1040 nm. Thus, launching a pump power $P_p \gg P_{sat}$ into a short length of fibre, the output emission will predominantly be at 974 nm. As the fiber length is increased, at first the gain and consequently the output power will increase. However, increasing the fiber length decreases the pump intensity at the output end and eventually a length is reached at which the exit pump power is just equal to P_{sat}. Lengthening the fiber further means that level c is no longer inverted with respect to a. The 974 nm emission will now see a net loss as it propagates through this portion. As far as the 974 nm emission goes the length $L_{opt,A}$ such that $P_p(L_{opt,A})=P_{sat}$ is the optimal one for maximum output power as further increases of the fiber length leads to reabsorption of the generated 974 nm radiation. This optimal length is of course a function of the launched pump power and increases with increasing pump power. For fiber lengths greater than $L_{opt,A}$, the gain medium will still be inverted with respect to transition B as long as ~4% of the ground state population is excited. If transition B were a perfect four-level transition there would be no optimal fiber length for this transition. If the fiber were longer than the length needed to completely absorb the pump light, the emission would simply propagate through the fiber without gain or loss. However, with the room temperature population of level b, the 1040 nm emission will be weakly absorbed if the entire fiber is not pumped. Thus, the fiber cannot be made arbitrarily long if maximum power is to be achieved. It should be added that reabsorption of the 1040 nm ASE at the unpumped end does not suppress ASE taking place at the input end. It simply reduces the amount of ASE which eventually exists as output. For the 974 nm emission the situation is complicated by the fact that its reabsorption pumps the inversion for the 1040 nm emission and by helping the 1040 nm emission it further reduces the 974 nm emission, since these two transitions also compete for the same upper state population.

Finally we note that shifting the pump wavelength away from the peak absorption tends to favor the 1040 nm emission since for the same pump power the bleaching is reduced (P_{sat} increases) and the gain for the 974 nm transition is affected to a greater degree than that of the 1040 nm emission.

3. Experimental details

The fiber used in these experiments had a doping level of approximately 575 ppm of Yb^{3+}, core diameter 3.7 µm and a cut-off wavelength ≃800 nm. Pump power was provided by a Styryl 9M dye laser tunable from 820–940 nm. A 18× microscope objective focused the pump light through a mirror butted to the input end of the fiber. The mirror had high transmission for the pump light but reflected >99% in the range 930–1200 nm. Its presence was, strictly speaking, not necessary, as single pass superfluorescence can be achieved. However, by collecting the backward fluorescence and adding it to the fluorescence output in the forward direction, the pump power requirement is reduced by a factor of two for the same gain. The output end of the fiber was terminated in index-matching liquid. This precaution was necessary for the purpose of producing a spectrally featureless superfluorescent output, since otherwise laser oscillation would occur via reflection from the fiber–air interface with corresponding longitudinal mode frequencies. The emitted light was collected with another microscope objective and sent through a monochromator (0.5 nm resolution) to separate the pump and emission wavelengths.

By cutting back a length of fiber while measuring the amount of transmitted pump power, the launch efficiency (pump power launched into fiber divided by the pump power incident on the microscope objective) was determined to be approximately 50%. This cut-back also indicated absorption coefficients of 40 dB/m at 900 nm and 2 dB/m at 850 nm. The power input for these measurements was kept well below P_{sat} at the input end to prevent bleaching.

To verify the expected qualitative behavior of the superfluorescent emission we first pumped a 3 m length of fiber at 900 nm, close to the absorption peak at 910 nm. This detuning was found to give more output power than pumping at the absorption peak, due to the higher pump powers available at 900 nm. This fiber was then cut back while monitoring the output power at the pump wavelength as well as at 974 nm and 1040 nm. For these measurements the amount of power incident on the input microscope objective was 60 mW, giving a launched power of 30 mW. Higher pump powers were available from the dye laser (see below), but rapid ageing of the dye and mechanical instabilities made it difficult to maintain these higher power levels for the duration of this part of the experiment. Fig. 2 shows a plot of power at the pump and emission wavelengths as a function of the fiber length. It is clear that the qualitative behavior is as described above, with the 1040 nm emission dominating completely for long lengths, while for shorter lengths the 974 nm emission is favored. We further note that the 974 nm emission peaks where the remaining pump power is 4 mW, in reasonable agreement with the estimate that $P(L_{opt}) = P_{sat} = 2$ mW.

Slope efficiency measurements were then carried out at the two wavelengths. For the 974 nm emission measurements a fiber length of 50 cm was chosen since, as seen in fig. 2, this was the optimum length for a launched pump power of 30 mW. Fig. 3 shows a plot of the measured output power versus absorbed pump power for this 50 cm fiber. A maximum fluorescence power of 10 mW was achieved, limited only by the available pump power. The data point giving 10 mW output was taken in an earlier measurement using fresh dye, thus permitting higher pump powers. The peak conversion efficiency of launched pump light into fluorescence is 33% and the slope efficiency measured at the peak power is approximately 43%.

For transition B the choice of fiber length is not critical. This transition can also be efficiently pumped at shorter wavelengths, where more pump power is available and where the 974 nm emission is discriminated against, as discussed earlier. Thus we pumped a 5 m length of fiber at 850 nm up to a maximum launched power of 80 mW. The output/input powers are plotted in fig. 4. A maximum output power of 27 mW is indicated there. Somewhat higher output powers were also achieved, up to 31 mW, but this required much more care in aligning the reflector at the front end of the fiber. It would probably be beneficial therefore to use a reflective coating applied directly to the fiber end, or by a mirror glued per-

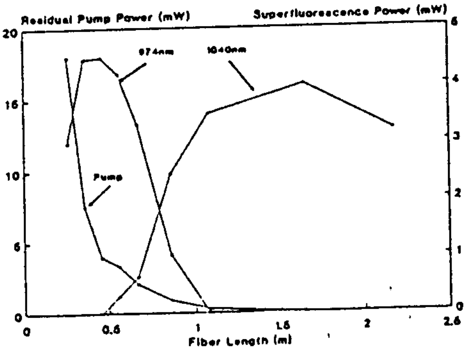

Fig. 2. Superfluorescent emission power and residual pump power versus fiber length for 30 mW pump power launched into the fiber.

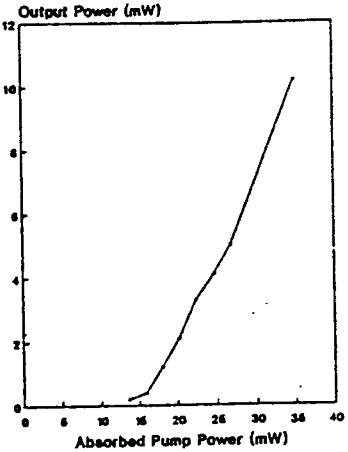

Fig. 3. Superfluorescence power at 974 nm versus pump power. Fiber length 50 cm, $\lambda_p = 900$ nm.

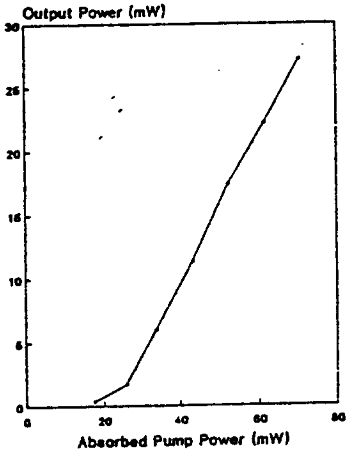

Fig. 4. Superfluorescence power at 1040 nm versus pump power. Fiber length 5 m, $\lambda_p = 850$ nm.

manently onto the end, as was done in ref. [3]. The peak conversion efficiency here is 34% and the maximum slope efficiency is 47%.

Emission spectra were taken at the two wavelengths. The 974 nm emission was typically 2 nm wide (fwhm) and without structure. The 1040 nm emission shows a complicated behavior in that the emission line center as well as the width can change with the pump power and pump wavelength. In the high power regime the emission is centered close to 1038 nm, but the width (fwhm) is typically 9 nm when pumped at 900 nm and 19 nm when pumped at 850 nm. As the pump power is decreased in the latter case, the peak gradually shifts to 1052 nm well below threshold. This behavior is suggestive of a site-dependent emission effect such as has been described in Nd fibers in ref. [4] and is the subject of further continuing measurements.

4. Discussion

We have shown that Yb-doped SFL's can provide efficient wavelength conversion to 974 nm and 1040 nm. The output powers and slope efficiencies on both transitions are among the highest reported to date for rare-earth doped fiber sources. The ultimate limit on the slope efficiency is $\lambda_{\text{pump}}/\lambda_{\text{signal}}$, i.e. 92% and 81% for 900 nm pumping of the 974 nm transition and 850 nm pumping of the 1040 nm transition. When pump/signal overlaps are taken into account [1], these reduce to 86% and 76%, respectively. The slope efficiencies we have observed are around half these values, a discrepancy which is as yet unexplained. Excited state absorption (ESA), a common cause of reduced efficiency in other lasers, is not responsible, since there are no energy levels appropriately situated. In fact the absence of ESA is an attractive feature of this laser, offering the possibility of wide tuning [6] and the prospect of scaling to much higher powers.

Besides the potential use of the SFL in sensor applications the 974 nm transition is of interest, either as SFL or as a laser with two feedback mirrors, for pumping of erbium doped fiber lasers and amplifiers. While erbium doped fiber is of considerable interest for telecommunications because of its emission at 1.55 µm, its shortcoming has been the lack of a pump band which is accessible to convenient pump sources and also is free from ASE of the pump. The absorption band centered near 980 nm has recently been identified as the optimal one from the point of view of avoiding ESA. This band is typically 40 nm [11] wide and thus the 974 nm light can be efficiently used for pumping. Rather than use the Yb-laser in the SFL geometry, it is likely that a conventional fiber laser resonator would be used. We have found that when pumped at 900 nm and the uncoated fiber end is used as a ~4% reflector, the laser threshold is 11 mW of power launched into the fiber and the slope efficiency reaches 67%. Detuning the pump laser to 850 nm and using a 25% reflector at the output end increases the launched power threshold to 30 mW. We expect that optimization of the output coupling will lead to a lowered threshold. Operation with laser diodes or diode arrays at 850 nm or longer wavelengths thus become a possibility.

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