MEASUREMENTS OF FIBRE LASER LOSSES VIA RELAXATION OSCILLATIONS

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We describe a simple method for measuring fibre laser losses. The method is based on inducing relaxation oscillations by modulating the laser gain. From the oscillation frequency and known fibre parameters a loss figure can be extracted. Loss measurements performed on a Nd-doped fibre laser are presented.

1. Introduction

Fibre lasers offer several advantages over bulk lasers. One appealing feature of fibre lasers, which results from the small pumped area of the active core, is that high gain can be achieved for small pump powers. This has made it easy to pump fibre lasers with low power diode lasers. It also means that one can hope to achieve lasing on transitions which would not normally be considered – in particular transitions with small quantum efficiencies and consequently small gains.

In either case it is important that excess resonator losses be minimised. These losses include those related to imperfect mirror coupling, intrinsic fibre losses due to scattering and absorbing impurities and reabsorption at the lasing wavelength. While low fibre loss can readily be achieved and reabsorption can be minimised by the correct choice of fibre length, losses due to imperfect coupling of end mirrors have to date been a source of uncertainty.

Fibre laser cavities have been constructed in several configurations. Open cavities (mirrors not in contact with the fibre ends) have been successfully used, but it is clear that lower losses can be achieved by butting or evaporating dielectric coatings directly onto one or both ends of the fibre.

To date there have been few published reports of fibre laser loss measurements. A recently published paper [1] described one way of measuring cavity losses. This method involved launching a short (150 ns) laser pulse at the intended laser wavelength into a very long (95.7 m) cavity and examining the transmitted power after the launched pulse made successive round-trips through the cavity. Thus the method gives a direct measure of the losses. However, it is limited by the need to use a resonator which is longer than the launched pulse width. Hence it is not easy to apply to most fibre lasers which typically have resonator lengths of a few metres or less. The method we report here does not suffer from this limitation, the measurement being made on the fibre laser under its actual operating condition. Furthermore, our technique does not require an external source of laser power aside from the pump laser for the fibre laser. In the case of the measurements reported here, the pump laser is a diode laser.

2. Measurement technique

The technique we have used is based on measuring relaxation oscillation frequencies as a function of pump power. It is well known that small temporal perturbations of a population inversion through perturbations in the pump power lead to laser power oscillations about the mean (relaxation oscillations). It can been shown [2] that for a 4-level laser the relaxation oscillation frequency can be written as

$$\omega^2 \simeq (1/P_{th}\tau_c\tau)P - 1/\tau_c\tau, \qquad (1)$$

where P = pump power, P_{th} = threshold pump power. τ = fluorescence life time and τ_c = cavity decay time. Plotting ω^2 as a function of P should then yield a

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straight line from which both the threshold power and the cavity decay time can be determined if τ is known. Once the cavity decay time has been determined the cavity loss can be found from [2]

$$\tau_c = -2L_{opt}/[c\ln(A)]. \tag{2}$$

Here L_{opt}=optical length of the cavity, c=speed of light and $A=R_1R_2(1-a)^2$, where $R_{1,2}$ are the two mirror reflectivities and a is the excess single pass loss.

It should be noted that eq. (1) is limited to a pure 4-level laser system. Equations valid for pure 3-level systems and quasi-3-level systems (where the lower laser level lies sufficiently close to the ground state to contain a non-neglegible thermal population) can be derived, but these cases will not be discussed here. We merely note that in the quasi-3-level case the lower laser level population acts as a fixed loss which modifies the right hand side of eq. (1). In our Nd fibre at room temperature the resulting correction factor to ω is only of the order of 1%. For longer fibres, more heavily doped fibres and systems where the lower laser level is closer to the ground level (in Nd it is >2000 cm^{-1} above ground), the correction factor can be significantly larger. Eq. (1) also assumes that the pump intensity does not significantly deplete the ground state population, so that the inversion is proportional to the absorbed pump power. This requirement is met in the laser system we have examined.

A further assumption in the derivation of eq. (1) is that the oscillations in laser intensity and population inversion are small compared to their steady state values and some care must therefore be taken to ensure that this condition holds in the measurements. Relaxation oscillations can be induced in several ways. With a sufficiently noisy pump laser, relaxation oscillations can be seen as ripples on the DC laser output initiated by this random noise. An alternative method is to induce oscillations by modulating the pump laser intensity using a mechanical chopper or by applying a square wave drive current to the laser diode. To avoid the large oscillations resulting from the use of a mechanical chopper, we modulated the diode current by applying a small square wave on top of a much larger DC level.

Finally we not that eq. (1) only holds for plane waves. In a fibre laser the spatial dependence of the pump and laser fields must be accounted for. This calculation has been carried out elsewhere [3] resulting in a multiplicative factor η on the right hand side of eq. (1) involving the spatial overlap of the pump and laser fields. The factor η is of the order unity, its exact value depending on the modes present.

We have performed measurements on a Nd-doped fibre laser with the following characteristics: laser wavelength=1.088 μm, fibre length L=5.5 m, τ=450 μs, doping concentration 300 ppm, refractive index=1.459, core diameter=3.5 μm and NA=0.21. The last two figures result in a correction factor η of 0.81. This value assumes single mode (LP$_{01}$) propagation at both pump and laser wavelengths. The cutoff wavelength of 0.92 μm ensured this for the fibre laser oscillation. Observation of the unabsorbed pump leaving the fibre showed that its mode structure depended on the launch conditions. It was, howeber, easy to adjust the launch so as to ensure LP$_{01}$ mode propagation for the pump. In preliminary experiments the fibre ends were cleaved with a hand tool, but this was found to give unsatisfactory results, i.e. high loss and unrepeatable performance. Subsequently the ends were epoxied into a glass capillary tube of inner diameter slightly (10–20 μm) larger than the fibre and the ends were polished to a high degree of flatness.

3. Results and discussion

The experimental setup is shown schematically in fig. 1. The laser was end pumped through a microscope objective by a 15 mW Hitachi laser diode emitting at 823 nm. The high reflector had R_1=99.5%, and the reflectivity R_2 of the output coupler was varied between 99.5% and 76%.

As was mentioned above, relaxation oscillations were induced by modulating the laser diode drive

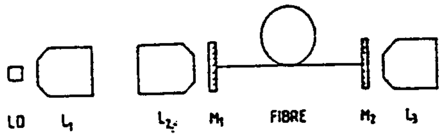

Fig. 1. Experimental set-up. LD=laser diode, L$_1$–L$_3$=18× microscope objectives, M$_1$=butted high reflector, M$_2$=butted output coupler.

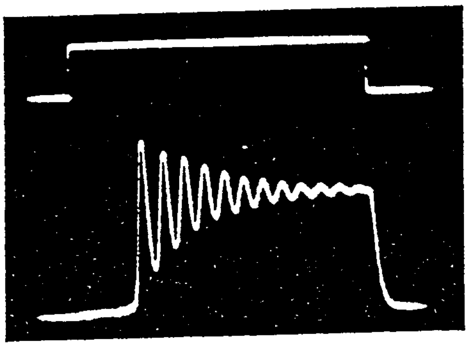

Fig. 2. Oscilloscope trace showing a typical train of relaxation oscillations, induced by current modulation of the pump beam. Upper trace – diode laser current. Lower trace – fibre laser output. Time base 200 μs/division.

current with a square wave. Fig. 2 shows a typical oscilloscope trace of the laser output in response to this modulated pump beam. The relaxation oscillations are very clean and stable and thus permit accurate frequency measurements.

Fig. 3 shows a plot of measured (relaxation oscillation frequency)^2 versus pump power for $R_2=99.5\%$ and 76%. As expected ω^2 is linear with P in both cases. From the ω^2-axis intercepts and the given fibre data we calculate excess losses of 6% and 10% respectively. These figures are calculated by assuming that reflections between the fiber end and the mirror do not alter the effective reflectivity of the mirror. In fact, one cannot separate the mirror loss from the coupling loss in these measurements. In the case of the high reflector, a highly multilayered dielectric structure, the influence of fibre-mirror reflections should be fairly small, its effect corresponding roughly to the removal of a single dielectric layer. The 76% reflector has fewer layers and thus butting a fibre to it may cause a significant change in its reflectivity. It is thus likely that the increased cavity loss with this output coupler is at least partly due to a reflectivity change.

It is notable that a system like the one in fig. 1 is susceptible to optical feedback into the pump laser, which may modify the output power and frequency of the pump laser. However, as long as the feedback does not modify the pump laser output in a nonlinear fashion, the net effect of feedback would be simply a linear scaling of the x-axis. This does not affect the ω-intercept and hence the loss measurements. The data shown in fig. 3 clearly show no evidence of nonlinearities.

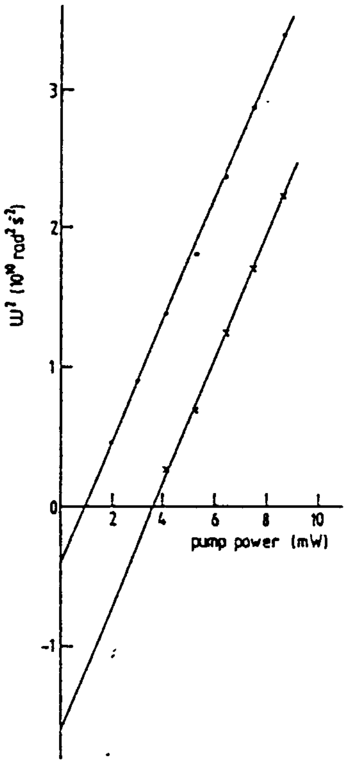

Fig. 3. (Relaxation oscillation frequency)^2 versus pump power for $R_2=99.5\%$ (•) and 76% (×). Threshold corresponds to $\omega=0$. Although the cavity loss is determined from the ω-axis intercept at $\omega^2<0$, negative ω^2 have no physical significance.

The losses presented here should not be seen as representing a lower limit on what can be achieved. Work is currently underway to improve the polishing techniques and this should result in much improved coupling. Lower losses have been reported elsewhere. Morkel et al. [1] have reported losses of 2% with cleaved fibre ends and Stone and Marcuse have shown [4] that coupling losses below 1% are possible if proper care is taken in preparing the fibre ends and in aligning the mirrors. Achieving losses down to the level of several percent is relatively straightforward, but a further reduction requires critical attention to several factors [5]. Aside from the obvious importance of minimising the fibre-mirror distance, the fibre end and mirror surfaces should be kept parallel to much better than one degree. At an even more rigorous level, losses due to the finite thickness of the mirror coatings, as well as small errors in the thickness of the various coating layers become limiting factors [5].

In our set-up with mirrors in physical contact with the fibre end, only mirror tilt was a controllable parameter and we have tested its influence on cavity losses. For these measurements the $R_2 = 99.5\%$ output coupler was used. Furthermore index matching fluid was applied between the fibre end and the mirror. If this precaution is not taken strong power fluctuations are seen as the fibre is moved into contact with the mirror, as mentioned above. This etalon effect is not necessarily detrimental to the laser action since the power output can be maximised by adjusting the fibre-mirror spacing. However, in these measurements it was deemed preferable to eliminate this interference in order that only coupling losses and known reflectivities were influencing the measurements. The measurements were done by first butting the two reflectors and measuring the cavity loss as described above. The output coupler was then moved a small distance away and a controlled tilt was imposed on the mirror. After butting the mirror again, the loss was remeasured and the whole process was repeated. In this way we were able to map out the loss as a function of the angular tilt.

The results of these measurements are shown in fig. 4. The results indicate that cavity loss can be sensitively dependent on mirror tilt, with a mere 1° tilt increasing the single pass loss by ~10%. In fact, the observed loss is due both to a tilt and an offset of the mirror from the end of the fibre resulting from our arrangement with the fibre mounted in a larger supporting capillary. A small tilt leads to a large offset and it is probable that the major contribution to the increased loss is from this offset.

4. Conclusion

We have demonstrated a simple technique for measuring losses in fibre laser cavities. The method permits in situ loss measurements to be made on virtually any 4-level laser and can also be applied to 3-level and quasi-3-level lasers with suitable modifications. We have presented measurements on a low loss (6%) Nd fibre laser cavity and have experimentally demonstrated the importance of controlling small mirror tilts in reducing the cavity loss.

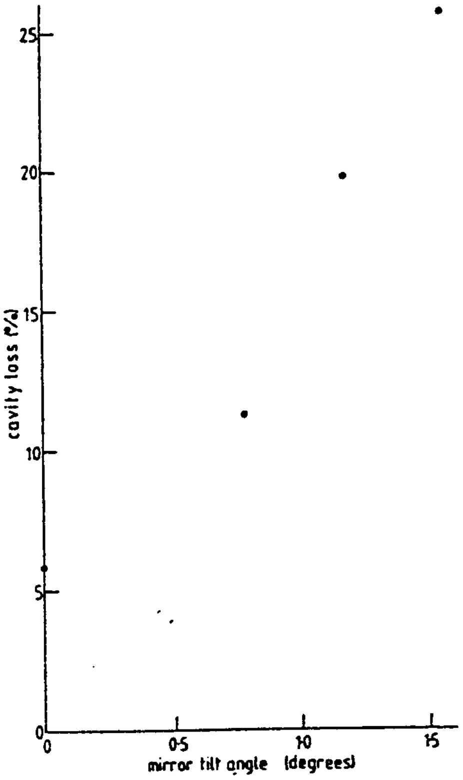

Fig. 4. Cavity loss as a function of output coupler tilt.

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