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LOSSES IN FIBRE LASER CAVITIES

Indexing terms: Lasers and laser applications, Optical fibres, Optical properties of substances

A passive cavity ring-down technique has been used to measure the intrinsic losses of a fibre laser cavity. The results show that very low cavity losses can be obtained using conventional mirrors butted to the fibre. Optimum output coupling for a typical cavity intrinsic loss is derived.

Continuous wave (CW) fibre lasers have been fabricated in a number of cavity configurations, including the direct butting of cleaved fibre ends against bulk-optic mirrors to form a Fabry–Perot resonator.[1] Although this technique is versatile, the optical loss incurred at the butted fibre ends has in the past been uncertain. For example, it is unclear whether the alternative technique of applying reflective coatings directly to the fibre ends[2] gives lower losses.

An indication of the excess loss of a laser cavity (i.e. excluding output coupling) is desirable in order to predict the optimum value of the output coupling. The optimum output coupling is defined as that which gives the maximum amount of laser output power for a given degree of pump power. We present in this paper results which give a direct indication of the excess loss in a butted-mirror fibre laser cavity, from which it is possible, using well known expressions,[3] to deduce optimum values of the output coupling.

The experimental configuration is shown in Fig. 1. A Q-switched Nd : YAG laser operating at 1·064 μm was used to inject pulses of 150 ns into the passive (i.e. unpumped) fibre laser resonator which contained Nd^{3+}-doped fibre. The fibre was characterised by an NA of 0·24, core diameter 2·7 μm, loss 4 dB/km and 500 ppm Nd dopant concentration. The cavity round-trip path length was chosen to be long (191 m) compared to the Q-switched pulse length in order to prevent any overlap effects within the fibre resonator. Each pulse from the Nd : YAG laser injected into the cavity shuttles back and forth and gives rise to an exponentially decaying train of pulses from the output mirror, as shown in Fig. 2. The spacing of the pulses gives the cavity round-trip delay time and the decay of the pulse envelope gives the round-trip feedback. To emphasise the effect of intrinsic losses, the two mirrors were chosen to have maximum reflectivity (>99·8%) at 1·064 μm. This necessitated the use of digital signal averaging of the Si : APD detector output to recover the small signal.

After an integer number N of cavity round trips the intensity feedback can be written as

$$\log_{10}(\text{feedback}) = N(-2\alpha L/10^4 + \log_{10}(R_1 R_2(1-k)))$$

where

α = fibre loss in dB/km
N = number of cavity round trips
L = fibre length
R_1, R_2 = mirror reflectivities
k = loss incurred at two mirror butts

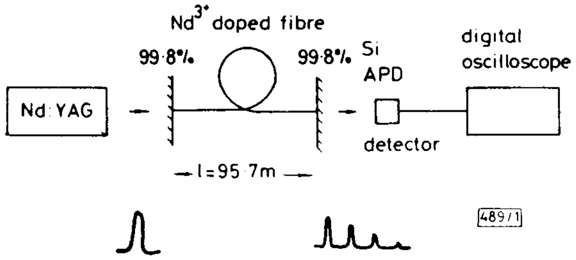

Fig. 1 *Experimental passive cavity configuration*

From the data in Fig. 2, $\log_{10}$ (feedback) can be plotted as a function of round-trip number and the result is shown in Fig. 3. The slope of the line gives the round-trip loss, from which, knowing the fibre loss to be (4 ± 0·5) dB/km, we can deduce that in this case $k < 4\%$. Thus each individual butt loss represents a loss of less than 0·1 dB.

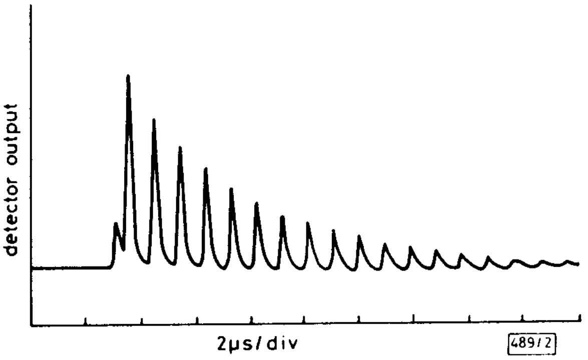

Fig. 2 *Detector output showing pulse decay within fibre cavity*
First peak due to stray light pickup from Nd : YAG laser

The butt loss was found to be highly dependent on fibre cleave quality, as expected. However, the measurement was repeated a number of times, using a York FK11 fibre cleaver to prepare two fresh fibre ends each time. Fig. 4 shows the measured butt losses (i.e. both fibre ends) for five separate consecutive cleave sets. The individual butt loss was found to be only 2 ± 1·5%, thus demonstrating excellent repeatability. The sensitivity of the measurement to fibre end preparation suggests that measurements of cavity ring-down may find more general application in assessment of cleave quality.

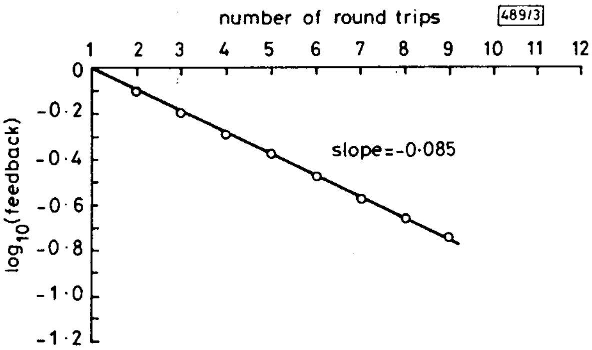

Fig. 3 *Plot of $\log_{10}$ (feedback) against number of round trips*
Data taken from Fig. 2

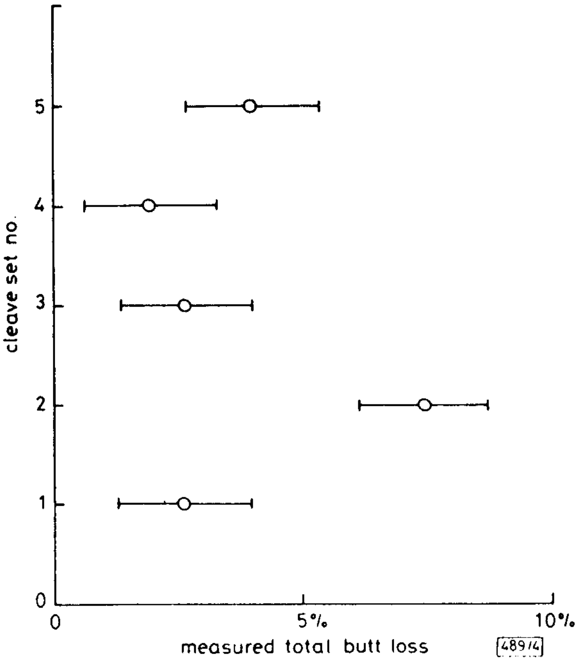

Fig. 4 *Measured butt losses for five consecutive cleave sets*

Using the well known expression for optimum output coupling T_{opt} in low-loss laser cavities, $T_{opt} = (g_0 L_i)^{1/2} - L_i$,[3] we can plot the optimum output coupling as a function of unsaturated gain per pass g_0 in nepers (typically 0–3 for Nd fibre under laser diode pumping), Fig. 5. This expression is derived for gain saturation with homogeneous line broadening, but is also applicable to inhomogeneously broadened systems subject to fast cross relaxation,[4] such as Nd-glass. For short lengths of fibre, around 1–2 m, the fibre loss becomes negligible and the excess cavity loss L_i is dominated by the butt losses. Hence we see that for an unsaturated gain of three and for cavity excess loss of 4%, the optimum output coupling is ≃30%. This figure is in good agreement with our previous empirical determinations using a range of mirror reflectivities.

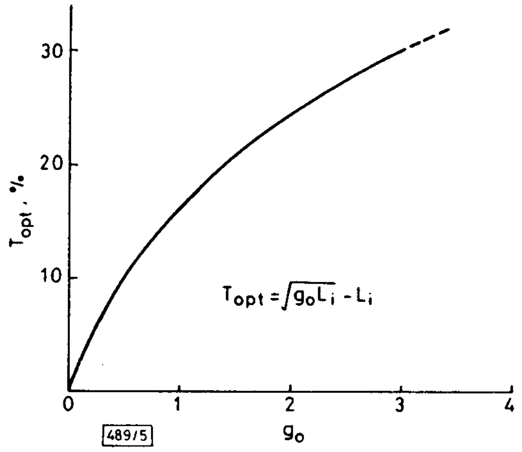

Fig. 5 *Optimum output coupling for a fibre laser against unsaturated gain per pass g_0 (in nepers)*
Excess loss $L_i = 4\%$

In conclusion, using a simple technique we have determined the butt loss in fibre laser cavities to be small when using a high-quality commercial fibre cleave tool. In addition, using the fibre butting technique it becomes possible to assess the butted cleave quality *in situ* and, if necessary, recleave the fibre before permanently fixing the fibre to the mirror. This enables very low butt losses to be obtained (less than 0·1 dB). Applying coatings direct to the fibre ends will not allow for this fine tuning of the cavity loss and will not in general provide such low-loss cavities.

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25th November 1987

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MICROWAVE PERFORMANCE OF PULSE-DOPED-HETEROSTRUCTURE GaInAs MESFETs

Indexing terms: Semiconductor devices and materials, Transistors, Microwave devices and components

A pulse-doped-heterostructure GaInAs MESFET having a 0·7 μm gate length with a transconductance of 270 mS/mm has been fabricated. Maximum stable gains of 14 dB at 26·5 GHz, which extrapolates to an f_{max} of over 100 GHz, were measured.

The high electron mobility of GaInAs and high saturation velocity of InP make these materials attractive alternatives to GaAs for high speed digital and monolithic microwave integrated circuits. Using these materials, it is possible to monolithically integrate optoelectronic devices, operating at a wavelength of 1·5 μm, and amplifiers on the same substrate. The low Schottky barriers on InP and GaInAs make it impossible to fabricate high performance MESFETs on these materials. Two alternative devices for overcoming this problem are the MISFET and a MESFET with an undoped AlInAs layer under the gate. In spite of the large gate voltage swing achievable in MISFETs, these devices are plagued by poor long-term stability of the drain current. MESFETs with undoped surface layers are superior to conventional MESFETs because they have higher cutoff frequencies, larger barrier heights, and higher breakdown voltages. Hida *et al.*[1] fabricated such MESFETs on GaAs substrates; we have developed similar MESFETs on InP substrates.[2]

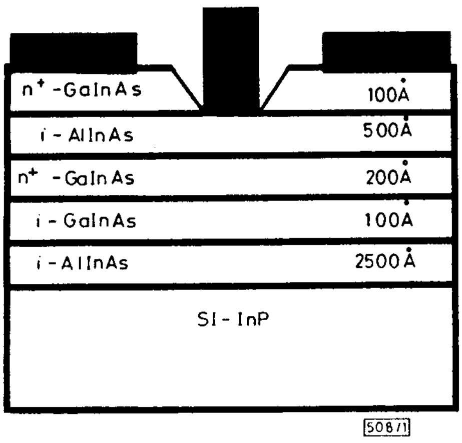

Fig. 1 *Cross-section of pulse-doped-heterostructure MESFET*

The MESFET structure grown by MBE (Perkin Elmer 425 B) is shown in Fig. 1. In this structure, the channel is a highly doped layer of GaInAs, which is 200 Å thick, and has a carrier concentration of $4 \times 10^{18}\,cm^{-3}$. The undoped AlInAs surface layer results in a higher Schottky barrier with a correspondingly reduced gate-leakage current. A Hall mobility of $4300\,cm^2/Vs$ with an electron concentration of $3{\cdot}2 \times 10^{12}\,cm^{-2}$ was measured at 300 K. MESFETs were fabricated using our standard processing sequence.

A peak extrinsic transconductance of 270 mS/mm was obtained for a 0·7 μm gate length device. The high-bandgap AlInAs layers confine the carriers, which explains[1] the broad peak in the transconductance against gate voltage of Fig. 2. This characteristic of the MESFET results in improved linearity for high power FETs. The microwave performance of this MESFET for different source–drain voltages was measured

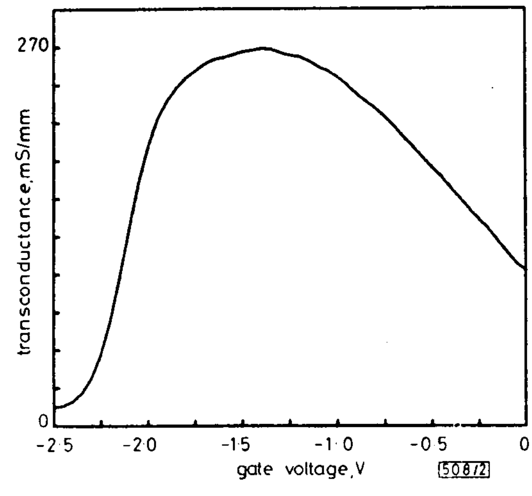

Fig. 2 *Transconductance against gate voltage of an n^+-GaInAs channel MESFET*