ACCURATE TUNING OF A LASER MODE-LOCKING DEVICE

Indexing terms: Laser modes, Tuning

Two simple methods are described for accurately tuning a mode-locking device for a laser. The first is suitable for an acoustic diffraction cell and involves a simple measurement of the diffracted light. The second can be used with any type of active mode locking and requires only a photodiode and a simple low-frequency spectrum analyser.

It is well known[1, 2] that, if the loss of a laser cavity is modulated at a frequency (or a harmonic of it) equal to the axial intermode spacing given by $c/2L$, where $c = 3 \times 10^8$ m/s and L is the equivalent free-space optical length of the cavity, the output becomes mode locked. Ideally a train of optical pulses is obtained at a repetition rate $c/2L$, or a multiple of this, and of a duration which is determined by the number of modes which are locked. In this way, pulses of widths between 1 ns and 1 ps or less can be obtained and either passive or active mode locking can be used, depending on the net gain and the laser. An active mode-locking device which is widely used is the acoustic diffraction cell.[1] Acoustic waves are set up in a suitable material so that energy is periodically diffracted out of the laser cavity, thus introducing a time-dependent loss.

We have used a block of fused silica on which is mounted a quartz transducer. On applying a suitable electrical signal to the transducer, standing waves are set up in the block at frequencies centred at 30 MHz, which is the driving frequency to the acoustic diffraction cell, and these set up longitudinal compression waves, and thus nodes of refractive index, separated by 100 μm. Light is therefore diffracted out of the laser cavity at all times except when the acoustic amplitude is instantaneously zero. By mounting the cell in a laser cavity near one of the mirrors, a shutter is provided which opens, or at least provides minimum loss, at a rate of 60 MHz. If the cavity length ($\simeq 2\cdot 5$ m) is such that the axial mode separation is also 60 MHz, mode locking occurs. However, if the acoustic cell is not accurately tuned, or if the modulation depth is insufficient, the cavity resonances are only partially phase locked, with the result that the pulse width is not at a minimum and, in addition to the pulses, there is a background level of unmodulated c.w. power. Thus the mode-locking efficiency is low and the pulse power is reduced.

One method of optimising the locking process is to observe the pulse shape with a fast detector and oscilloscope and to adjust the frequency of the driving power to the acoustic cell, or more conveniently the mirror separation, for maximum pulse height. This method has its difficulties; for example, it requires the use of a sufficiently fast detector and oscilloscope and is obviously not suitable for ultrashort mode-locked pulses, and we have carried out experiments with two other, more sensitive, methods, one of which is particularly simple.

In the first of these, a detector, which need only indicate average power, is placed so as to intercept the laser power in the 1st-order diffraction beam from the acoustic cell; i.e. emerging at an angle to the laser axis of $\sin^{-1}(\lambda/d)$ where λ is the optical wavelength and d is the separation between acoustic nodes in the cell. As mode-locking action builds up and the energy in the laser cavity condenses into a

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single pulse, which passes through the acoustic cell when the standing-wave intensity is zero, the energy diffracted out of the cavity falls to a very low level. Thus the cavity length is finely adjusted until the detector reading falls sharply to a minimum as synchronised mode locking is achieved.

The second method is also applicable to other methods of active mode locking and involves displaying the beat spectrum of the oscillating modes of the laser with a photodetector and an r.f. spectrum analyser.* To check the results the laser output was also displayed on a 25 ps-risetime sampling oscilloscope.† Fig. 1 shows the 633 nm-wavelength output of the He–Ne laser as a function of time and frequency, when no synchronising signal was applied to the acoustic cell. Passive mode locking occurred at c/L, twice the fundamental rate, although frequency components at $(2n-1)(c/2L)$ were present as well. In order to display the entire beat spectrum, only a portion of which is shown in Fig. 1*b*, a display bandwidth of about 1 GHz is required. However, for the present application, it is only necessary, and indeed is much more convenient, to display one beat component, requiring a display bandwidth of between 0·1 and 1 MHz, as in Fig. 1*c*. This shows the lowest beat component on an expanded frequency scale. The lineshape is noisy, and has a width of about 60 kHz.

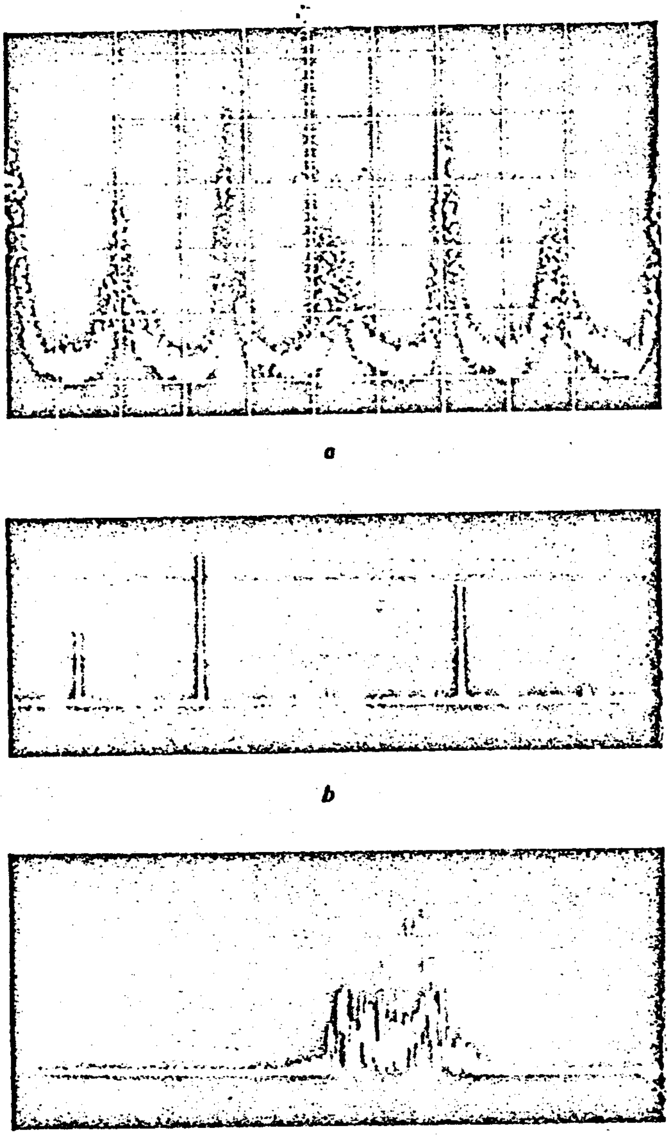

Fig. 1 *Passive mode locking*

a Sampling oscilloscope trace of passively mode-locked-laser output at a sweep speed of 5 ns/cm
b Lower portion of the beat spectrum to a scale of 32½ MHz/cm with an i.f. bandwidth of 10 kHz
c Expanded sweep of lowest beat component to a scale of 32½ kHz/cm

When the synchronising signal was applied to the acoustic cell at approximately the correct frequency, sidebands to the (noisy) beat components appeared. Figs. 2*a* and *b* show these sidebands about the lowest beat component when the loss modulation frequency is low and high, respectively. It may be seen that one sideband is noisy while the other is clean and distinct, and also that, when the loss modulation frequency is too low, the clean sideband is at a lower frequency than the main component and vice versa. Thus this method has the distinct advantage over the time-domain display that it is easily seen whether the locking frequency is high or low, and also by how much. An explanation of the nature of these sidebands is given below. As the modulation frequency approached the correct value for locking, the sidebands drew nearer the main beat component and ultimately merged with it, giving the appearance of a noisy carrier, as in Fig. 3*a*. However, when mode locking occurred, the noise disappeared and the beat component became clean, sharp and of increased amplitude as in Fig. 3*b* and *c*.

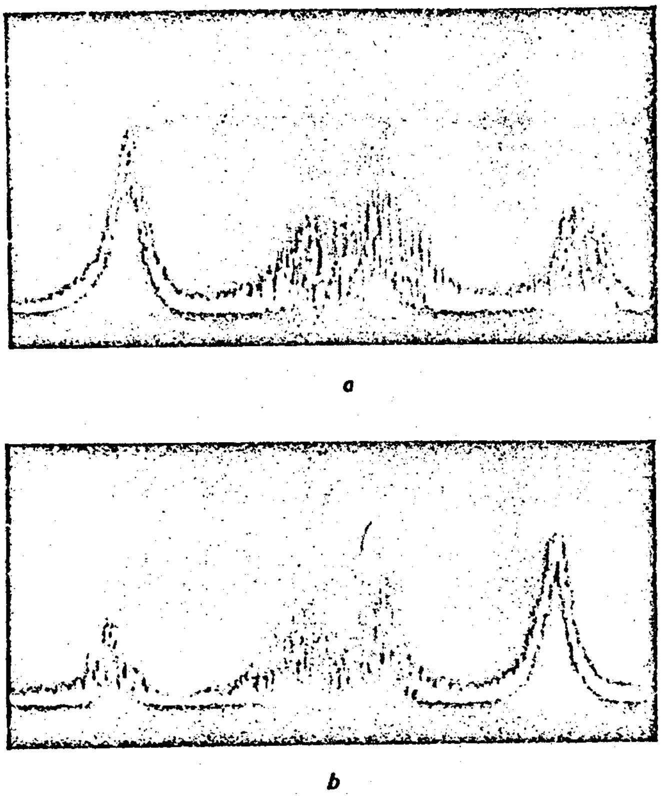

Fig. 2 *Sidebands about lowest beat component when the loss modulation frequency is 100 kHz (i.e. 0·16%) too low (a), and too high (b), for active mode locking to occur*

The halfwidth of the spectral line (about 10 kHz) in Fig. 3*b* is determined by the bandwidth of the spectrum analyser. In further experiments using a low-frequency spectrum analyser tuned to the intermediate frequency (5·3 MHz), of a superheterodyne receiver‡ much narrower linewidths were obtained. For example, the 60 MHz fundamental beat component of the actively mode-locked laser now had a measured halfwidth of 200 Hz. Since this was exactly that of the oscillator providing the synchronising signal, the latter is obviously the factor limiting the frequency stability of the mode-locked output which must be within 1 in 3×10^5. It was found that the accuracy of mode locking could be judged to within 100 Hz with a spectrum analyser but not with a time-domain display. A similar effect has been observed with passive mode locking[3] when the cavity length was tuned. In our case the cavity length remained fixed at the optimum value for active mode locking at a loss modulation frequency of 59·238 MHz, and a much higher degree of resolution was obtained.

A time-domain trace of the actively mode-locked pulse train is shown in Fig. 4*a*, and the expanded trace of Fig. 4*b* shows that the halfwidth of the pulses is 700 ps. The latter is probably limited by the fluorescence linewidth of the

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* In our experiments, a Tropel 0·3 ns risetime silicon *p-i-n* photodiode and Hewlett-Packard 8551B spectrum analyser were used

† Tektronix 561B main frame, with 352 sampling unit, S-4 sampling heads and 3T77A sweep unit

‡ Eddystone 770R receiver and Tektronix 1L10 spectrum analyser

neon lasing transition.

Some explanation is required for the apparently surprising spectra shown in Fig. 2 where the main component is very noisy whereas one of the sidebands is comparatively noiseless. The situation in a free-running laser which is not mode-locked, and to which loss modulation has been applied, is rather complicated. The various axial modes suffer a degree of frequency pulling which depends on their distance from the line centre. The fundamental beat 'component' produced by a photodiode thus consists, in fact, of a number of components, no two of which, in general, are at the same frequency, due to beats between pairs of adjacent axial modes which are at different separations. The axial modes, being unlocked, drift relative to each other in both amplitude and frequency, giving rise to the wide and noisy central component. The 'clean' sideband is unaffected by the relative drift of the various axial modes, since it is due to mixing between each axial mode and the side components on it which are produced by the loss modulation. The other sideband, however, is again directly affected by the relative stability of the axial modes, since it is due to beats between each mode and the lower (higher) sideband due to loss modulation of the next-but-one higher (lower) mode. Similar arguments apply to all of the beat components. The complete frequency spectrum thus consists of a series of noisy carriers, each having one noisy sideband and one clean sideband. When active mode locking occurs, each axial mode becomes locked to its neighbours at a frequency separation equal to that of the loss modulation. A stable clean-line spectrum is then obtained, a portion of which is shown in Fig. 3*c*.

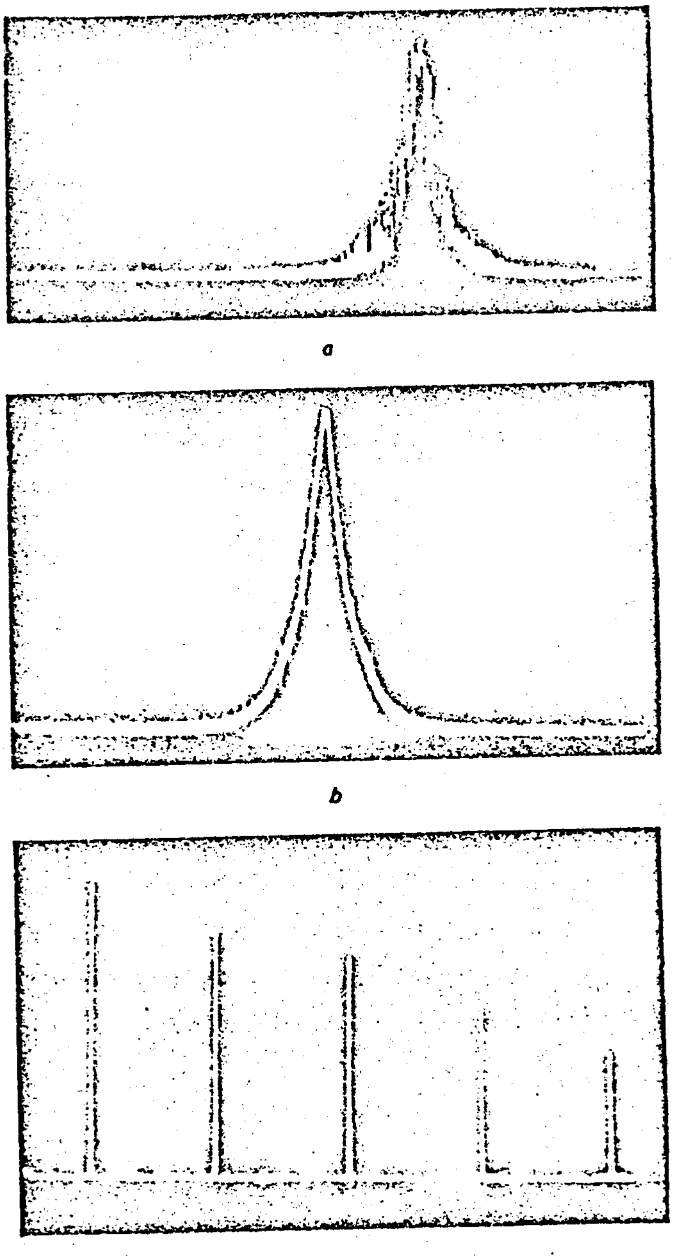

Fig. 3

a Lowest beat component with loss modulation frequency 6 kHz (i.e. 0·01%) too low for active mode locking to occur. Horizontal scale: 31½ kHz/cm
b Lowest beat component with active mode locking. The linewidth and the i.f. bandwidth of the spectrum analyser are 10 kHz
c Lower five beat components with active mode locking. Horizontal scale: 31½ MHz/cm

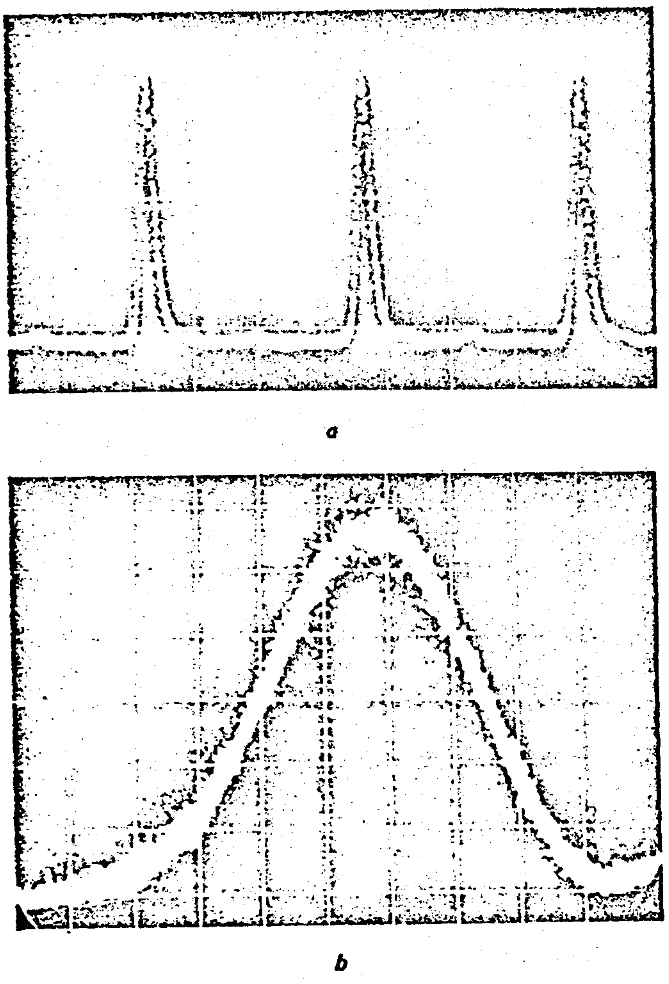

Fig. 4

a Output of actively mode-locked laser with a sweep speed of 5 ns/cm
b Expanded trace of a single pulse with a time scale of 200 ps/division

Conclusion: Two simple methods of tuning a laser mode-locking device have been described. With an acoustic diffraction cell, a simple c.w. measurement of the diffracted light is sufficient. The second method uses only a photodiode and a low-frequency spectrum analyser to observe one beat component of the axial modes. The position of the noise-free sideband indicates immediately the amount and sign of the frequency offset, while the sudden reduction of the noise on the single-frequency component indicates clearly and accurately the onset of active mode locking. Similar effects were observed with other beat components.

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W. A. GAMBLING
P. J. R. LAYBOURN
M. D. LEE*
H. SUNAK
M. ANSON

Department of Electronics
University of Southampton
Southampton SO9 5NH, England

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* Now with the Plessey Co., Poole, Dorset, England