Passive and active mode locking of a semiconductor laser without an external cavity

K. Y. Lau and I. Ury
Ortel Corporation, 2015 West Chestnut Street, Alhambra, California 91803

A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received February 1985; accepted for publication 12 March 1985)

This letter describes the first attempt to passively and actively mode lock a discrete semiconductor laser, i.e., one not coupled to an external cavity. Beat notes of the longitudinal modes of a 1.97-mm-long GaAlAs laser have been observed at 17.7 GHz. The spectral width of the beat note was approximately 100 kHz. Stable passive mode locking has been observed under appropriate operating conditions. Active mode locking by an externally injected microwave signal was also achieved.

The technique of mode locking of a semiconductor laser diode, actively or passively, has involved to date the coupling of the laser to an external cavity.[1] This is necessary in order to reduce the free-spectral range of the laser, which for a discrete device with a usual cavity length of 300 μm lies beyond 100 GHz, to the vicinity of the frequency range (a few gigahertz) where the laser has a reasonable modulation response. In this letter we describe the first observation of passive as well as active mode locking in a discrete (i.e., no external cavity) 1.97-mm-long semiconductor laser, which produces stable intensity oscillation in the optical output at 17.7 GHz. The intensity oscillation is more sinusoidal than pulse-like, with a modulation depth of less than 100%, indicating that only a small number of modes are locked. The dominant mechanism for producing mode locking is believed to be due to localized saturable absorbing centers in the laser cavity. The parameters of the gain and absorber media are apparently not optimal for complete mode locking (short-pulse generation) in this first experiment, although in some potential applications of this type of device in millimeter wave technology as described later in the paper, frequency stability rather than optical pulse width is the major concern.

The laser used in this study is a large optical cavity buried heterostructure laser otherwise similar to the one used in previous high-frequency laser studies.[2] The cw threshold current for lasing generally lies between 10 and 20 mA for this type of device with a cavity length of 300 μm, and the differential quantum efficiency is typically 0.4 mW/mA. The cw lasing threshold and differential quantum efficiency of a 1.97-mm-long device are, as shown in Fig. 1, 73 mA and 0.13 mW/mA, respectively. The decrease in differential quantum efficiency is a direct result of increased total scattering and absorption losses of the longer waveguide. The length of 1.97 mm is chosen to give a cavity mode spacing of approximately 17 GHz. The lasing spectrum consists of a number of longitudinal modes, as shown in Fig. 2. The mode spacing $\Delta\lambda$ of approximately 0.42 Å corresponds to a Δv of 17.6 GHz. The laser is mounted in a high-frequency package. The optical output is detected by a high-speed GaAlAs *pin* photodiode with a -3 dB bandwidth of 14 GHz, whose output is displayed on a microwave spectrum analyzer (Hp 8410). With the laser operating cw and without any external modulation, the microwave spectrum of the photodiode output shows a very narrow spike at a frequency of 17.7 GHz due to the beating between the longitudinal modes. The spike is very unstable, with its amplitude fluctuating at random between the instrument background noise level (-72 dBm @ 100-kHz resolution bandwidth) and ~ 12 dB above the noise background. This is interpreted as a result of the random drifting of the relative phases of the longitudinal modes which, under uniform current injection and in the absence of external modulation, have no means for phase locking to one another. The very narrow linewidth ($\sim$ 100 kHz) of the beat signal is due to the correlation between the phase fluctuations of the longitudinal modes of a semiconductor laser, and will be discussed in detail separately.[3]

The direct modulation response of this laser shows a relaxation oscillation peak at a frequency of up to 2.5 GHz at a bias optical power of 12 mW. (Incidentally, the relaxation oscillation frequency of a similar laser of 300-μm length, at similar bias optical power level, is $\sim$4 GHz.) Beyond approximately 10 GHz the modulation response is so weak as to be undetectable on the microwave spectrum analyzer. However, the modulation response peaks up sharply by more than 10 dB above the instrument noise level in a narrow band of $\pm$ 4 MHz around 17.730 GHz, where the modal beat signal occurs. The amplitude of the modulation

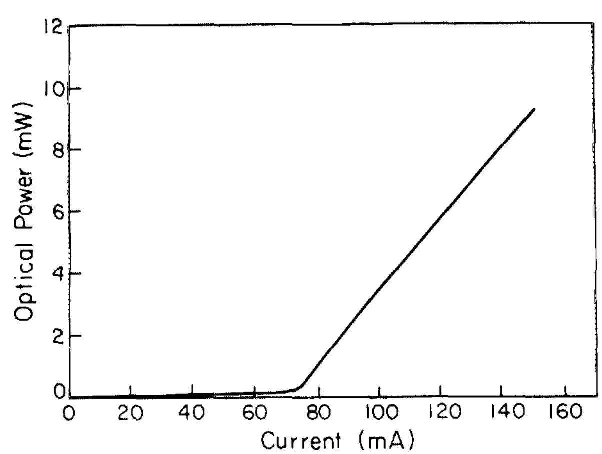

FIG. 1. Light output vs input current characteristic of a 1.975-mm-long buried heterostructure GaAlAs injection laser pumped uniformly over the length.

 0003-6951/85/121117-03$01.00

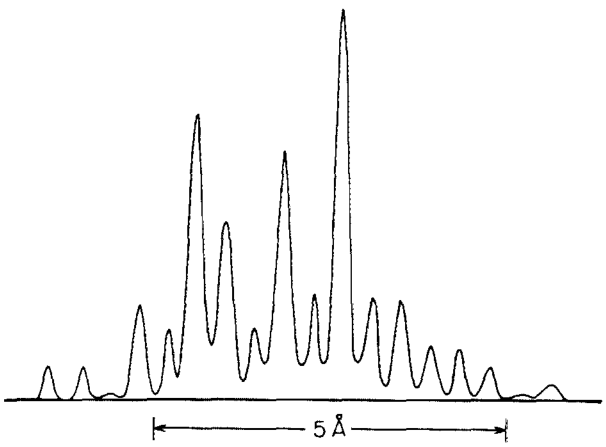

FIG. 2. Spectrum of the optical emission.

response also fluctuates, although not as much as in the case of the intrinsic beat signal. These observations point to incomplete active mode locking, even at a microwave drive power as high as + 18 dBm.

The phenomena described above occur over a range of bias power level from ~9 up to ~17 mW. However, a significant qualitative change occurs when the laser is momentarily brought close to the catastrophic damage power level. When the laser is then biased to emit an optical power of ~16 mW, the erratic noise spike at around 17.730 GHz observed previously is replaced by a stable although broader peak as shown in the top picture (a) of Fig. 3. Further increases in bias current result in the displays shown in (b) and (c) of Fig. 3. The spectral lines shown in these displays are very stable, in total constrast to the previously mentioned erractic behavior. There is also a slight shift in the frequency of the spike towards the lower end as the current is increased. When the bias optical power is reduced to below ~16 mW, the laser reverts to its previous "unlocked" state.

One possible explanation for the above observed result is that as the laser power approaches the catastrophic damage level, facet degradation occurs which leads to formation of saturable absorbing defects near the mirror facet. This fact is well documented and is thought to be responsible for self-pulsation in semiconductor lasers,[3,4] as well as for picosecond pulse generation in external cavity mode-locking experiments.[5] The presence of localized saturable absorption inside the laser cavity can lead to passive mode locking, which establishes a fixed relationship between the longitudinal modes and consequently leads to a well-defined intensity oscillation in the laser output. There are, of course, constraints on the properties of the absorber and the gain medium in order for passive mode locking to take place.[6] Although the properties of the defects near the facet are not well established, the above experimental observation as well as previous external cavity passive mode-locking experiments suggests that such conditions could well be fulfilled over a certain range of pump current. The shift of the noise spike to lower frequencies at increased pump level is consistent with the increase of the refractive index of the laser material as the pump level is increased, although a change in the cross sections and time constants of the active media due to a change of injection current could also be responsible.

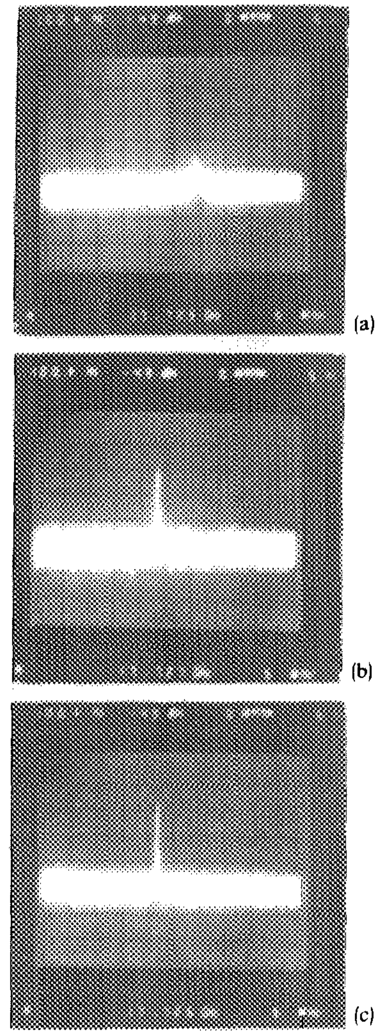

FIG. 3. Microwave spectrum of the photodetector output at three different bias optical powers when the laser is in the "locked" state. (a) 16 mW, (b) 16.5 mW, (c) 17 mW. Horizontal: center frequency 17.725 GHz, 5 MHz/div.

The modulation depth of the intensity oscillation can be estimated from the observed microwave signal amplitude from the photodiode and the dc photocurrent, taking into account the frequency response calibration of the photodetector. The modulation depth obtained is ~25%. It is thus expected that the intensity waveform is more sinusoidal than pulselike. This, as mentioned before, indicates locking of only a small number of modes as a result of unoptimized material parameters.

When an external microwave signal is injected into the laser under the passively locked condition, the injection locking phenomenon shown in Fig. 4 is observed. The microwave drive applied to the laser is at 18 dBm, the maximum power available from the oscillator (Hp83595). This is in essence active mode locking of the laser, although it should be noted that this could not be achieved without having the laser operating in the passively mode-locked state so that it could perhaps be better described as synchronously pumped, or hybrid passive-active, mode locking. It is difficult to achieve mode locking in this device by purely active means because (a) the modulation response of the laser at 17.7 GHz is extremely weak and (b) the modulation current is injected

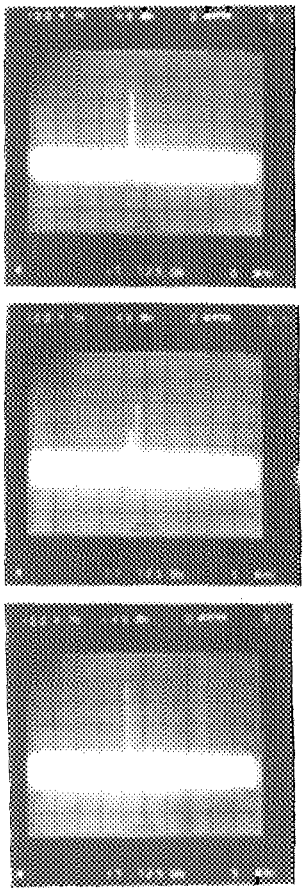

FIG. 4. Injection locking by modulating the injection current with an external microwave signal at 18 dBm. Horizontal: center 17.725 GHz, 5 MHz/div.

uniformly over the single-contact device and therefore fails to fulfill a necessary condition for active mode locking.[7] The results shown in Fig. 4 follow the general behavior of injection locking in oscillators.[8] A sweep of the injected signal frequency produces Fig. 5, which shows the (-3 dB) locking bandwidth to be approximately ± 1 MHz.

One potentially important application of this type of untrahigh frequency mode-locked laser devices in microwave and millimeter wave technology is as follows. Solid state microwave and millimeter wave sources such as Gunn or IMPATT oscillators are generally quite noisy, and might well be described as narrowband noise sources. A stable, narrow-linewidth signal can be generated from these sources when placed in high-Q metallic resonators, which are bulky and expensive at millimeter wave frequencies. Similar results can be accomplished by locking the solid-state oscillator in a feedback loop to a stable, narrow linewidth source, of which a mode-locked laser (with a linewidth of less than 100 kHz as described above) is an ideal choice. This concept has been demonstrated recently[9] by using a self-pulsating GaAlAs laser to lock a Gunn oscillator in the lower GHz range. The entire oscillator system could be hybridized in a compact, miniature package or can possibly be monolithic. It should be noted that since virtually all millimeter wave components and systems operate in limited frequency bands, short optical pulse generation is generally *not* a prerequisite for the optical device to be used in the type of application described above.

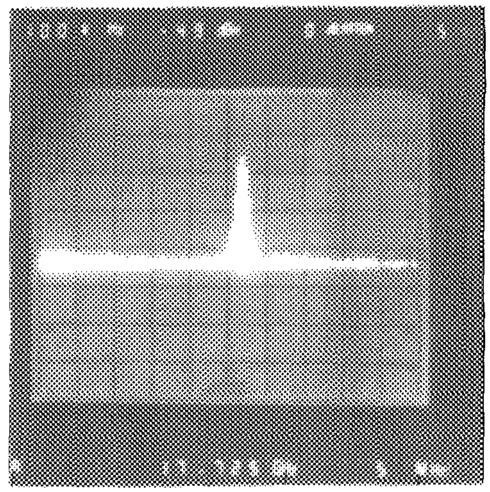

FIG. 5. Response of sweeping the external injected signal frequency across the intercavity mode frequency, showing the injection locking bandwidth. Horizontal: center 17.725 GHz, 5 MHz/div.

The passive mode-locking technique described above depends on defects introduced by operating the laser very close to catastrophic damage and is therefore not very reliable. An alternative is to introduce segmented contacts with independent current control to effect a localized absorbing region in the cavity.[10] It should also be possible to use alternative absorbers to effect a more complete mode locking (and therefore generate short pulses). Recently reported candidates such as proton bombardment or quantum well structures should be integrable into a single monolithic laser structure. Nevertheless, the first observations described above are encouraging and it would seem conceivable that passive mode locking can take place at even higher frequencies well into the millimeter wave region, in semiconductor lasers of shorter cavity lengths. This would bring optical techniques into the realm of millimeter wave technology and could open up whole new areas of application of semiconductor lasers. Whether there are fundamentals limitations as to the highest attainable frequency is not clear at this point.

This work is supported by the Defence Advance Research Project Agency and Naval Research Laboratory.

[1]E. P. Ippen, D. J. Eilenberger, and R. W. Dixon, in *Picosecond Phenomena II*, edited by Hochstrasser, Kaiser, and Shank (Springer, New York, 1980), and references therein. More recent experiments in high-frequency mode locking are seen in R. C. Alferness, G. Eisenstein, S. K. Korotky, R. S. Tucker, L. L. Buhl, I. P. Kaminow, and J. J. Veselka, paper WJ3, Optical Fiber Communication Conference, New Orleans, 1984; R. S. Tucker, G. Eisenstein, and I. P. Kaminow, Electron. Lett. **19**, 552 (1983); K.Y. Lau and A. Yariv, Appl. Phys. Lett. **46**, 326 (1985).

[2]K. Y. Lau and A. Yariv, IEEE J. Quantum Electron. **QE-21**, 121 (1985).

[3]K. Vahala, K. Y. Lau, and A. Yariv (unpublished).

[4]H. Kressel and J. K. Butler, *Semiconductor Lasers and Heterojunction LED's* (Academic, New York, 1977), Chap 16; R. W. Dixon and W. B. Joyce, IEEE J. Quantum Electron. **QE-15**, 470 (1979).

[5]J. P. Van der Ziel, J. Appl. Phys. **53**, 4435 (1981).

[6]H. A. Haus, IEEE J. Quantum Electron. **QE-12**, 169 (1976).

[7]A. Yariv, *Quantum Electronics* (Wiley, New York, 1975), also T. L. Koch, Ph.D. thesis, California Institute of Technology 1982, Chap. 6.

[8]K. Kurokawa, Proc. IEEE. **61**, 1386 (1973).

[9]S. H. Izadpanah, Z. Rav-Noy, S. Margalit, and A. Yariv, Appl. Phys. Lett. **45**, 609 (1984).

[10]Ch. Harder, K. Y. Lau, and A. Yariv, IEEE J. Quantum Electron. **QE-18**, 1351 (1972).