Mutual phase locking of a coupled laser diode-Gunn diode pair

S. H. Izadpanah,[a] Z. Rav-Noy, S. Mukai, S. Margalit, and Amnon Yariv
California Institute of Technology, Pasadena, California 91125

(Received 9 May 1984; accepted for publication 3 July 1984)

Mutual phase locking has been achieved through series connection of a semiconductor laser and a Gunn diode oscillator. Experimental results obtained demonstrate a mutual interaction between the two oscillators which results in a short term Gunn diode oscillator stability and improved spectral purity of its output. We also observe a narrowing of laser pulses and an improvement in regularity.

It has been demonstrated that injection locking by modulated laser beams can give rise to major improvements in the stability and spectral purity of a number of solid-state microwave oscillators which include Gunn and Impatt diodes as well as field-effect transistor oscillators.[1–5] It is not surprising to find, as we will show in what follows, that injecting a microwave current into a self-pulsating semiconductor laser diode stabilizes and narrows the laser intensity pulses when the microwave and the pulsation frequencies are (nearly) harmonically related.[6,7] It would follow then that, if we form a closed loop in which the microwave current of a solid state oscillator is injected into a laser diode, while, at the same time, part of the laser diode light output is intercepted by the oscillator, then both sets of benefits should occur simultaneously. That is, in such an arrangement we should observe a narrowing of the microwave spectrum of the oscillator and a temporal narrowing and stabilizing of the laser pulses.

The experimental arrangement used to test the premises advanced above is shown in Fig. 1. It consists of a GaAlAs buried heterostructure laser on semi-insulating substrate[8] with threshold current of 12.5 mA. Self-pulsation was induced in these otherwise well-behaved lasers by momentarily bringing the lasers beyond the catastrophic damage level. It must be emphasized here that it is not necessary for one to induce damage to a laser for it to self-pulse; a highly reliable way of accomplishing the task is by a double contact laser structure reported previously.[9] The frequency of pulsation varies with the pump current (i) following a $\sqrt{i - i_{\rm th}}$ dependence.

The solid-state oscillator was a planar Gunn diode fabricated from wafers with n^+/n layers grown by liquid phase epitaxy on semi-insulating substrates. The layers had a thickness of $n^+ = 0.2\,\mu$m (10^{18} cm^{-3}) and $n = 2.5$–$3.0\,\mu$m (4×10^{16} cm^{-3}). The n^+ contact layer was removed above the active region. The active layer was mesa etched with a 25–30-μm width and a length of 30–40 μm defined by Au/Ge contacts alloyed to the n^+ layer. The diodes were mounted on a pedestal situated at the juncture of two converging microstrips transmission lines. The diodes had an oscillation threshold of 10–14 V with a transit time frequency of 2.3–2.9 GHz.

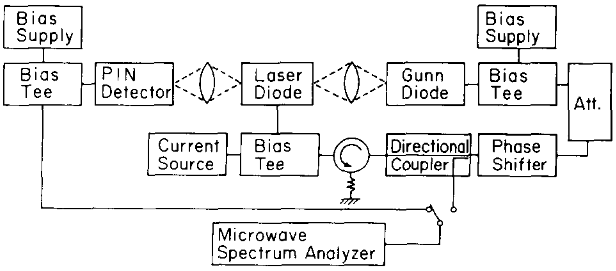

FIG. 1. Circuit arrangement for mutually locked laser diode/Gunn diodes pair.

The microwave current of the Gunn diode was injected into the laser through a bias "*T*," an attenuator, and a phase shifter. The laser output was focused onto the anode region of the Gunn diode. Pulse illumination of the anode region reduces its local field due to carrier generation; this produces a transient increase in the cathode field which synchronizes the domain formation.

We first operated the laser alone (no bias applied to the Gunn diode) in the self-pulsating mode. The microwave spectrum of the pulses as detected by a fast *p-i-n* photodiode is shown in Fig. 2(a). The fundamental pulsating frequency is close to 1.249 GHz and up to six harmonics are detectable. The spectrum of the fundamental frequency on a 10-MHz/div scale is shown in Fig. 3(a). The full width at half-maximum of this spectrum is $\simeq$18 MHz. Next the laser is turned off and the Gunn diode is biased at 10.6 V producing a transit time oscillation at 2.45 GHz. A typical free-running spectral width for the Gunn oscillation in this case was approximately 600 kHz. Finally we ran the Gunn oscillator simultaneously with the laser diode. By adjusting the laser current

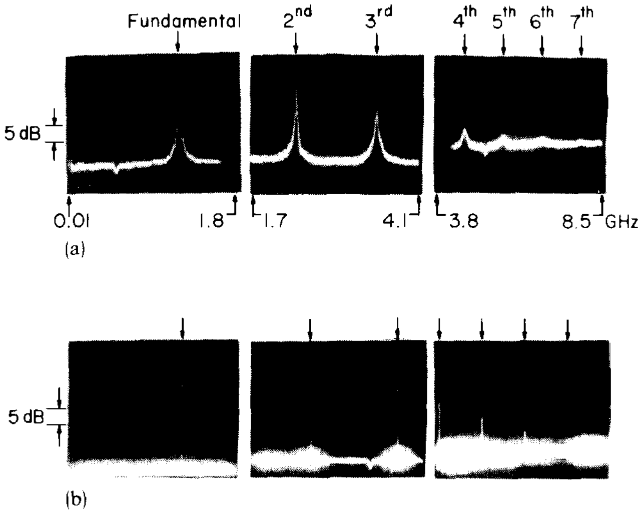

FIG. 2. Microwave spectrum of self-pulsating laser diode: (a) free-running and (b) under locking condition.

---

[a] Lightwave Technologies, Inc., Van Nuys, CA 91406.

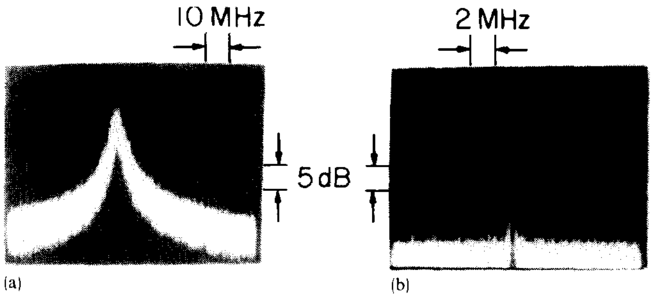

FIG. 3. Spectrum of laser fundamental pulsating component: (a) free-running and (b) locked pulsation.

and the Gunn voltage, the second harmonic of the laser pulsation frequency and the Gunn oscillation frequency could be made to approach each other. As soon as these two frequencies are within a typical range of 2–5 MHz, the laser pulsation frequency is pulled and locked to the Gunn oscillation with the laser pulsating at half the Gunn oscillation frequency. Concurrently a considerable decrease (×36) in the spectral width and an increase in the harmonic content of the laser pulsation are observed. This indicates a narrowing of the laser pulses and an improved regularity of its pulsation. The determination of the harmonic content of the laser intensity pulsation is limited by the detector response and indicates optical pulses below 30 ps. Figure 2(b) shows the spectrum of the laser pulsation under locking conditions. The spectrum of the fundamental component of the laser intensity pulsation after locking is shown in Fig. 3(b). A photograph of the Gunn spectrum in the locked and unlocked cases is shown in Fig. 4. The locking causes the spectrum to narrow from 600 to nearly 250 kHz. This indicates that the parasitic oscillating signals in free-running Gunn diodes are partially suppressed. When the light reaching the Gunn diode is blocked, the following changes are observed. (a) The Gunn oscillation frequency drops to a value of 2–3 MHz below its locked value, and its spectral width reverts to the larger free-running value. (b) Depending on the setting of the phase shifter and attenuator, which determine the locking range, the laser pulsation can be made to remain locked to the Gunn oscillator or to unlock with an associated spectral width increase to the free running value.

In conclusion, initial experimental results obtained from an optoelectronic loop consisting of a coupled self-pulsating laser diode Gunn diode pair indicate that the mutual interaction between the two oscillators results in a short term Gunn diode oscillator stability and improved spectral purity. The laser pulses become narrower and the pulse train regularity is greatly enhanced.

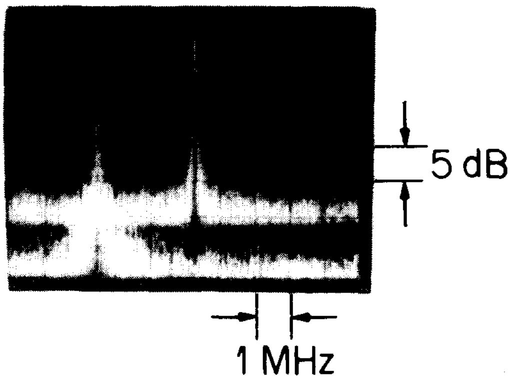

FIG. 4. Microwave spectrum of Gunn oscillation: (a) free-running and (b) locked via laser pulses.

The potential benefits are twofold. (1) A monolithically (or hybrid) integrated optically coupled laser diode can be used, instead of a cavity, to stabilize the oscillation of Gunn diodes or other microwave oscillators. (2) The same combination can be used to improve the pulsating regularity of laser diodes used as sources in an optical communication or sampling applications. By controlling the bias condition of the laser diode (Gunn diode), one can affect a tuning of the Gunn (laser) oscillating (pulsation) frequency.

This research was supported by the Office of Naval Research, the Air Force Office of Scientific Research, and from a research grant from the International Telephone and Telegraph Corporation.

[1] K. Kurokawa, Proc. IEEE **61**, 1386 (1973).
[2] H. W. Yen and M. K. Barnoski, Appl. Phys. Lett. **32**, 182 (1978).
[3] H. W. Yen, Appl. Phys. Lett. **36**, 680 (1980).
[4] A. A. Salles and J. R. Forrest, Appl. Phys. Lett. **38**, 392 (1981).
[5] L. Goldberg, C. Raucher, J. F. Welles, and H. F. Taylor, Electron. Lett. **19**, 848 (1983).
[6] T. L. Paoli and J. E. Ripper, IEEE J. Quantum Electron. **QE-6**, 335 (1970).
[7] T. L. Paoli and J. E. Ripper, Appl. Phys. Lett. **16**, 96 (1970).
[8] K. Y. Lau, N. Bar-Chaim, I. Ury, Ch. Harder, and A. Yariv, Appl. Phys. Lett. **43**, 1 (1983).
[9] Ch. Harder, K. Y. Lau, and A. Yariv, IEEE J. Quantum Electron. **QE-18**, 1351 (1982).