Novel Optical Control Techniques for Solid-State Radar Transmitters

RICHARD A. KIEHL, MEMBER, IEEE

***Abstract*—New optical techniques for performing the RF control functions needed for such applications as short-pulse and phased-array radar transmitters are described and demonstrated. The techniques utilize optical signals to directly control the internal operation of a solid-state oscillator by the photoexcitation of carriers within the active region of the oscillator. Short RF pulse generation is achieved by making use of the subnanosecond optical power rise time of a laser diode to rapidly quench the RF output of a microwave oscillator. Phase control of a microwave oscillator is achieved by a phase-locked-loop (PLL) scheme wherein the loop is completed by an optical signal that directly controls the output frequency.**

I. Introduction

THERE HAS been a recent exploration of the use of optical techniques for performing the various RF control functions needed for such applications as short-pulse and phased-array solid-state radars. Direct optical control of semiconductor oscillators is produced by the photoexcitation of free carriers within the active region of the device. Optical control is the result of the sensitivity of the device's oscillatory dynamics to photoinduced changes in the internal carrier densities. Optical techniques have attracted interest largely because of their ultimate speed capability and their effectiveness in controlling high-power and highly nonlinear oscillators. This interest has been augmented by the rapid advance of laser diode technology, which makes optical techniques of practical interest for miniature component development.

Schemes for short RF pulse generation utilize rapid optically induced changes in the amplitude of the RF output of such oscillators as avalanche diodes [1], [2]. Either an enhancement or a quenching of the oscillation can be produced during an optical pulse depending on the oscillator-circuit tuning. The enhancement of the oscillation during a short optical pulse is the more direct approach for short-pulse generation. However, it is the quenching mode that has been more readily obtained experimentally, and theory shows [3] that such behavior is to be expected in general. Therefore, a less direct, but possibly easier, approach would be to make use of oscillation quenching in some way. One obvious way to do this would be to utilize an optical signal that is "on" except within a narrow time window. Unfortunately, the generation of such an optical signal with high-power laser diodes is quite difficult compared to the generation of simple optical pulses.

From the foregoing, one concludes that a scheme for short-pulse generation that utilizes the quenching mode while still employing optical pulses would be most attractive. In the first part of this paper we describe such a scheme. Specifically, in Section II we describe a short-pulse generator that employs an optically quenched IMPATT oscillator together with a simple signal processing scheme. A key feature of our approach is that it makes use of such laser processes as "lasing delay" and mode-locking to produce optical pulse rise times, and hence RF pulsewidths, that are much shorter than the rise times or pulsewidths of the electrical drive signals.

Control of the phase of the microwave output has recently been demonstrated [4], [5] with an optical injection locking scheme analogous to conventional injection locking. Such phase control is of particular interest for solid-state phased array systems. In optical injection locking, an optical signal modulated at the oscillation frequency (or a subharmonic thereof) is used to periodically perturb the oscillator, thereby causing the phase of the oscillation to lock to that of the optical signal envelope. The locking of transistor oscillators operating at 2 GHz with optical signals modulated at frequencies as low as 100 MHz has been demonstrated [4] with this method.

The second part of this paper deals with an alternate optical technique for phase locking. Rather than utilizing the injection locking scheme described above, the approach taken here is to devise a phase-locked loop (PLL) in which the loop is completed by an optical signal that directly controls the oscillator's output. The phase locking of a high-power TRAPATT oscillator with a low-power laser diode by this technique is described in Section III.

Finally, concluding remarks and a discussion of the ultimate potential of these techniques are given in Section IV.

II. Short RF Pulse Generator

The scheme for generating short RF pulses is illustrated in Fig. 1. A microwave oscillator is rapidly quenched by a fast rise time optical pulse, and the RF output is split between two paths having transit times which differ by T. The signals in these two paths are then subtracted to produce the final RF output. The subtraction results in a cancellation of the output prior to the quenching of the oscillation, thus resulting in the generation of a narrow

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The author is with Sandia Laboratories; Solid State Device Physics, Division 5133, Albuquerque, NM 87115.

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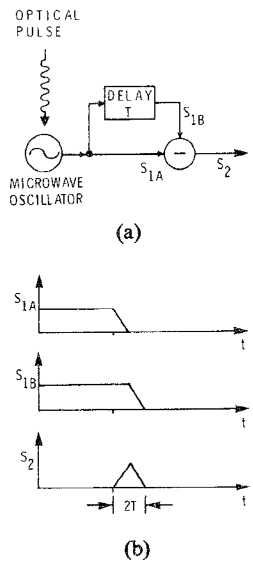

Fig. 1. Short RF pulse generator based on an optically quenched IMPATT oscillator. The output from the oscillator is split into two signals which travel different path lengths and are then subtracted.

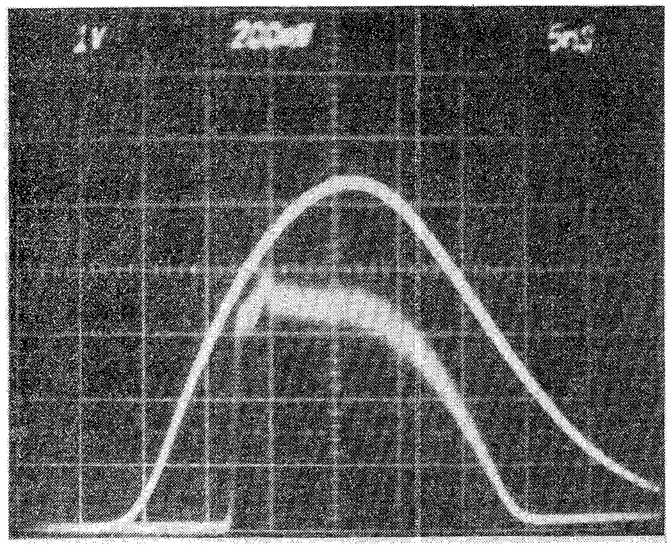

Fig. 2. Drive current (top) and detected optical output (bottom) for a pulsed GaAs laser diode. Due to the "lasing delay," the optical power rise time is much shorter than that of the drive current. Vertical: 10 A/div., uncal.; Horizontal: 5 ns/div.

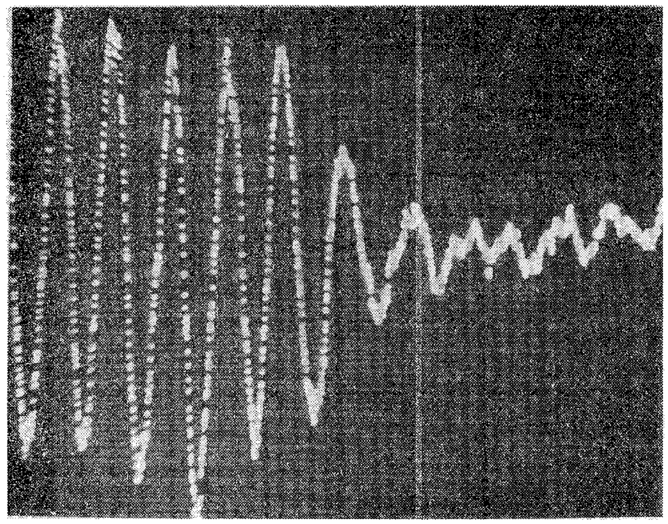

Fig. 3. Output of an IMPATT diode illustrating the rapid quenching produced by a short rise time optical pulse. Vertical: uncal.; Horizontal: 0.2 ns/div.

RF pulse. Due to the signal splitting, the peak power of this pulse is one-half the oscillator power. The power level preceding the pulse will depend on the completeness of the signal cancellation at the subtractor, while the level following the pulse will depend on the degree of quenching. The minimum pulsewidth occurs when the delay time T is equal to the oscillation quenching time, resulting in a pulsewidth of $2T$, as illustrated in the figure.

While this "delay-and-subtract" signal processing scheme can be used in conjunction with any technique for oscillator turnoff, the attractiveness of optical quenching for accomplishing the turnoff is that the turnoff time can be made very short, thus making possible the generation of very narrow RF pulses. Due to the characteristic "lasing delay" process found in pulsed laser diodes [6], the light output rise time can be made much shorter than the risetime of the bias current itself. This is illustrated in Fig. 2, which shows the generation of an optical signal having a 0.4-ns rise time with an electrical signal having a rise time of 22 ns. By exploiting this effect, optical power rise times of 0.1 ns or less have been obtained [7] with commercial high-power GaAs laser diodes. Furthermore, the speed with which a semiconductor oscillator can respond to the light pulse is also fast, due to the rapid change in internal carrier densities. In the case of the IMPATT oscillator examined in this work, the optically generated carriers can serve to change the device conductance from a large negative value to a large positive value [3], thereby not only preventing the device from supporting oscillations, but acting to Q switch (dampen) the microwave cavity as well. As a result, the turnoff time is not limited by the cavity Q and can be as fast as the rise time of the optical pulse itself. The speed as well as the repeatability of the quenching event is illustrated in Fig. 3, which shows a sampling oscilloscope display of IMPATT quenching produced by synchronizing short rise time optical pulses with the RF cycle.

The experimental configuration used to demonstrate this technique is shown in Fig. 4. The microwave oscillator consisted of an X-band silicon IMPATT diode mounted in a slug-tuned coaxial oscillator circuit. The contact metallization on the top surface of the mesa diode was a small dot 3 mils in diameter centered within the 10-mil diameter mesa. The diode was encapsulated in a ceramic package having a ring top cap. A small hole in the end of the coaxial circuit mated with the top cap, allowing the top surface of the mesa to be illuminated by an external laser diode positioned 0.5 cm from the IMPATT, as illustrated in Fig. 5. The laser was a single-heterostructure GaAs-GaAlAs diode (LD-68) emitting at 904 nm with an optical power of 2.8 W. Optical pulses of

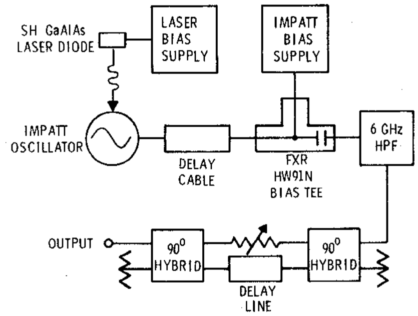

Fig. 4. Schematic diagram of the experimental apparatus used to demonstrate the short RF pulse generator.

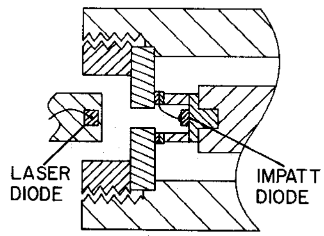

Fig. 5. Cross-sectional view showing the mounting of the packaged IMPATT diode chip in the coaxial circuit for illumination by an external laser diode. (Not to scale.)

20 ns in duration were produced using an avalanche transistor drive circuit similar to that described elsewhere [7]. In order to achieve a high peak power level, the IMPATT was also biased in a pulsed mode. The pulse bias level, pulsewidth, and repetition rate were 300 mA, 1 μs, and 200 pps, respectively. A prebias (dc bias) of 1 mA was also applied.

As shown in Fig. 4, the output of the coaxial circuit was connected through several feet of cable to an FXR HW91N bias tee followed by a 6-GHz high-pass filter. Pulsed illumination produces pulses in the IMPATT current which can be reflected back to the IMPATT plane by mismatches in the system (e.g., at the bias tee or filter), thereby disturbing the IMPATT's operation. While such reflections can be eliminated by proper matching, the approach taken here was to insert several feet of cable in order to delay the return of reflections for several nanoseconds after the quenching event. The high-pass filter was included to prevent the current pulses from reaching the RF detector at the output. The "delay-and-subtract" scheme was implemented using 90° hybrids, as shown in the diagram. The employment of hybrids for signal splitting and recombining was useful for isolating the two signal paths, thereby preventing spurious responses. The variable attenuator was included to allow the signals to be adjusted precisely for equal amplitude. In this way, a cancellation of the signals to a level of 40 dB could be achieved at the output. Note that due to the delay between the two signals, the degree of cancellation is frequency dependent and is, therefore, subject to degradation in the event of oscillator drift. This frequency sensitivity is not severe, however, when the delay time is small, as is the case in short pulse applications. For

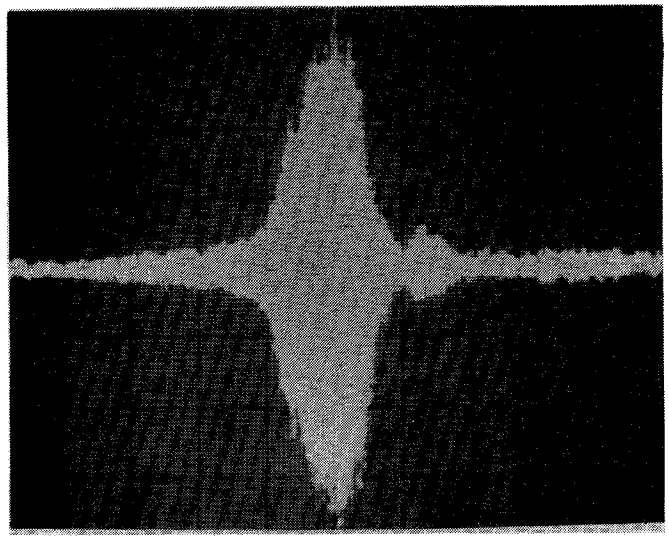

Fig. 6. Sampling scope display of the RF output of the system shown in Fig. 4. Horizontal: 1 ns/div.

example, a simple calculation shows that, at a nominal operation frequency of 9 GHz, a cancellation of 20 dB can be maintained over a frequency range of ± 0.7 percent for a delay time of 0.5 ns.

Fig. 6 shows the generation of short RF pulses by the above scheme, as displayed on a 12-GHz bandwidth sampling oscilloscope. The IMPATT frequency and RF power were 8.4 GHz and 1.2 W, respectively. The optical pulse had a 10–90-percent rise time of 0.4 ns and produced a peak radiant flux density of 180 W/cm^2 at the IMPATT diode's surface. Examination of the display shows that the achieved RF rise and fall times are approximately equal to the 0.4-ns rise time of the optical pulse itself, thus representing about 3 RF cycles. The pulsewidth at the 10-dB points is 1.5 ns. The gradual increase in signal level preceding the RF pulse is the result of a small shift in oscillation frequency produced by the low-level spontaneous emission that precedes lasing in the GaAs laser diode. Since the spectrum of this spontaneous emission is much wider than that of the stimulated emission, it should be possible to eliminate this effect by the use of a narrow-band interference filter. Even with this effect, however, it is still possible to maintain an on/off ratio of about 20 dB with respect to the leading edge of the pulse. The small amplitude pulse that is seen trailing the main pulse reduces the on/off ratio for the trailing edge to 17 dB. This RF pulse is believed to be the result of a ringing of the IMPATT current produced by the excitation of a low-frequency resonance by the optically induced step in IMPATT current. Such an undesirable secondary pulse was not observed in experiments performed with lower power GaAs IMPATT diodes.

III. Optically Completed Phase Locked-Loop (PLL) Oscillator

We now turn to the use of optical signals for controlling the phase of an oscillator. One basic technique for phase control is the use of a PLL. In order to phase lock an

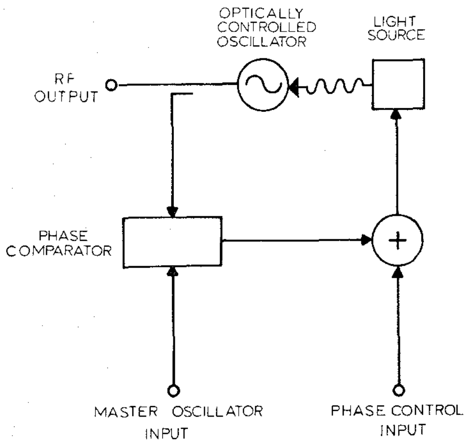

Fig. 7. Optically completed PLL oscillator.

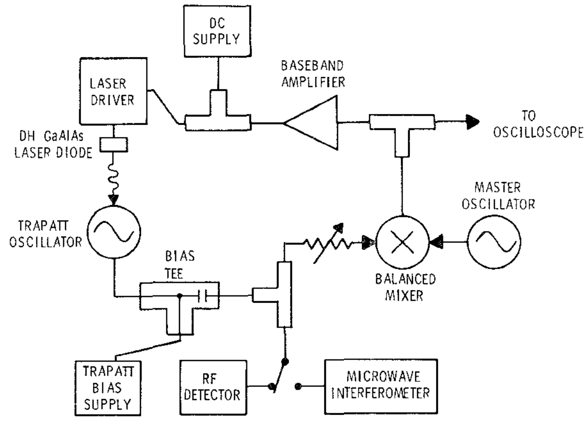

Fig. 8. Schematic diagram of the experimental apparatus used to demonstrate optically completed PLL phase locking.

oscillator by this technique, one needs a means for controlling the oscillator's frequency. While frequency control of many solid-state microwave sources can readily be achieved by conventional electrical pulling (varactor) or pushing (biasing) schemes, for some sources this is not the case. In particular, the high amplitudes and nonlinearities in the TRAPATT diode's waveforms hamper the use of pulling techniques, while the internal interplay of the plasma density and extraction rate limits the usefulness of pushing techniques for this device. Optical control, on the other hand, has been shown [8] to be quite effective with the TRAPATT oscillator. Hence, it is of interest to explore the use of optical techniques for phase locking this device.

An optically completed PLL is depicted in Fig. 7. As in a conventional PLL, the phase of the output signal is compared with that of a master oscillator, thus producing an error signal that is dependent on the phase difference between the two oscillators. This error signal is then used to intensity modulate a light source. The emitted optical signal is coupled into the microwave oscillator so as to drive the oscillation frequency up or down in accordance with the error signal, thereby completing the loop.

The experimental configuration used to demonstrate this technique is shown in Fig. 8. The TRAPATT oscillator consisted of a p^+-n-n^+ planar silicon diode mounted in a slug-tuned coaxial cavity. The diode was mounted on a small heat sink with the n^+ substrate down. Electrical connection was made to the p^+ layer by directly bonding a thin wire to the unmetallized p^+ surface. This allowed illumination of about 80 percent of the p^+ surface through an opening in the side of the coaxial circuit. Further details of the TRAPATT diode and oscillator circuit are given elsewhere [1]. The power level and instantaneous frequency of the oscillator were monitored by an RF detector and a microwave interferometer. Phase comparison of the oscillator output with that of an HP 8699B master oscillator was implemented with a Lorch FC 2182 balanced mixer. A wide-band operational amplifier (Analog Devices 50J) was included to permit the error signal to be adjusted to the proper input level for the laser driver circuitry. A variable dc current was added to the amplifiers output, allowing the locking phase to be adjusted over the range of 180°. (An additional 180° was obtainable by inverting the amplifier output.) The laser was biased by an emitter-coupled driver circuit similar to that described elsewhere [9]. The laser was a double-heterostructure GaAlAs diode emitting at 890 nm with a maximum optical power of 7 mW and was positioned 1.2 mm from the TRAPATT diode. This resulted in a maximum radiant flux density of approximately 3 W/cm^2 at the TRAPATT surface. The laser/driver combination permitted a modulation depth of about 12 dB to be produced in the optical output.

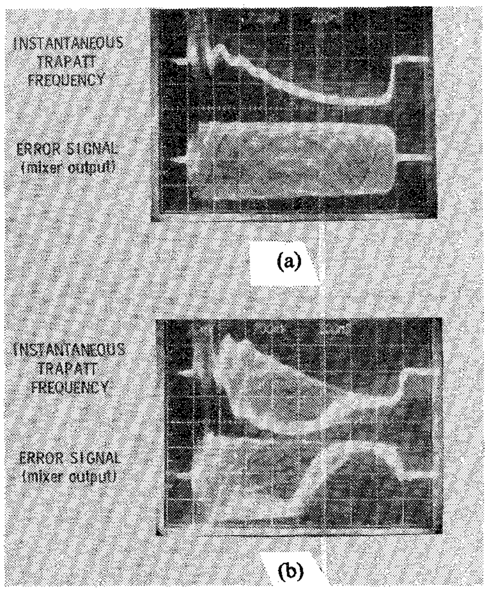

Fig. 9. Instantaneous frequency (top trace) and error signal (bottom trace) with loop. (a) Inoperative. (b) Operative. Vertical: 1.4 MHz/div., uncal.; Horizontal: 100 ns/div.

A demonstration of the phase-locking is shown in Fig. 9, where the instantaneous frequency (top trace) and error signal (bottom trace) are shown both for the case of an inoperative loop and for the optically completed loop. In this experiment the TRAPATT diode was pulse biased for

0.8 μs at a rate of approximately 100 pps, resulting in a peak RF power of 53 W at 0.73 GHz. For the inoperative case shown in the top of Fig. 9, the instantaneous frequency drifts downward gradually due to heating during the TRAPATT pulse. The photographs in this figure are multipulse exposures. Accordingly, the error signal indicates that the phase difference between the TRAPATT and master oscillator is random pulse-to-pulse, as would be expected. The bottom half of the figure shows that, when the loop is closed, the TRAPATT frequency is initially driven up-and-down by the intensity modulated optical signal and then remains constant as locking is achieved approximately 0.6 μs after the beginning of the pulse. The variation in RF power level caused by the varying optical signal was negligible. The locking range in this experiment was 4 MHz (0.5 percent) and was limited by the modulation depth and optical power level of the present laser/driver combination. Although an attempt was made to decrease the locking transient by adjusting the baseband amplifier bandwidth, it was not possible to reduce the transient below about 0.6 μs. In long-pulse ($\gtrsim$ 10-μs) operation, this transient would have little effect. For short-pulse operation, the locking transient could be removed from the output by gating.

IV. Conclusion

Novel optical techniques for generating short RF pulses and for phase locking an RF source have been proposed and demonstrated using commercially available laser diodes in combination with conventional solid-state microwave oscillators. The attractiveness of using optical pulses to form RF pulses by the technique described here is that this scheme should make possible the generation of exceptionally narrow pulses. Specifically, pulsewidths as short as 200 ps are feasible with present laser diode technology. Recent success in mode locking of laser diodes [10] could eventually allow even shorter pulsewidths to be achieved. Since the controlling device (the light source) is isolated from the RF energy, this technique will be particularly attractive for high-power short-pulse radars where conventional techniques are relatively slow due to inherent power-speed limitations.

The optically completed PLL extends the utility of the PLL principle to oscillators that are difficult to phase lock due to a poor response to electrical pushing or pulling techniques. The responsiveness of the TRAPATT oscillator to "optical pushing" has allowed PLL phase locking to be achieved with an optical signal level on the order of 1000 times lower than the RF output level. This means that, at least for this device, the practical implementation of this technique is possible with present laser and light-emitting diode technology. The optically completed PLL has advantages over recently proposed optical injection locking schemes in that the required control-signal modulation frequency is usually much lower for the PLL thereby simplifying the laser/driver design. This makes the present technique of particular interest for active phased-array radars where the operating frequency is high.

Acknowledgment

The use of the "delay-and-subtract" signal processing scheme was suggested by R. J. Chaffin. R. E. Hibray is also acknowledged for his work in the experimental measurements.

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