A 63-W *W*-Band Injection-Locked Pulsed Solid-State Transmitter

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***Abstract*—A high-power three-stage *W*-band injection-locked pulsed solid-state transmitter using four hybrid-coupled two-diode IMPATT power combiners as the final stage has been developed. Coherent peak output power of 63 W and 92.6 GHz was achieved. The transmitter was operated at 100-ns pulsewidth and 0.5-percent duty cycle. This transmitter development was directed at achieving a high-power output that would be useful for future millimeter-wave system applications.**

I. Introduction

THE RAPIDLY INCREASING demand in millimeter-wave radar systems has created an urgent need for a high-power *W*-band solid-state transmitter. Recently, a single silicon IMPATT diode has been reported to generate 13-W peak output power with 8-percent dc-to-RF conversion efficiency consistently [1]. To achieve even higher power output, two-diode and four-diode waveguide resonant cavity combiners have been developed with peak output power of 20 and 40 W at frequencies near 94 GHz [2]. This paper reports the development of a three-stage injection-locked pulsed transmitter that uses an eight-diode power combiner as the final power stage. The eight-diode combiner was constructed by hybrid coupling four two-diode waveguide cavity combiners. The transmitter was operated at 100-ns pulsewidth and 0.5-percent duty cycle. A stable CW source was used to injection lock a single-diode pulsed source, which in turn locked the eight-diode combiner to achieve a coherent peak output power of 63-W at 92.6 GHz with more than 70-percent combining efficiency. This achievement has proved the feasibility of jointly utilizing different combining techniques to achieve practical high-power coherent solid-state transmitters.

II. Multiple-Level Combiner Circuit

In practice, the maximum number of diodes that can be combined in the waveguide resonant cavity combiner is limited to four due to tuning and moding problems. The tuning of the cavity combiner, which is necessary to stabilize the desired oscillation, is accomplished by adjusting a

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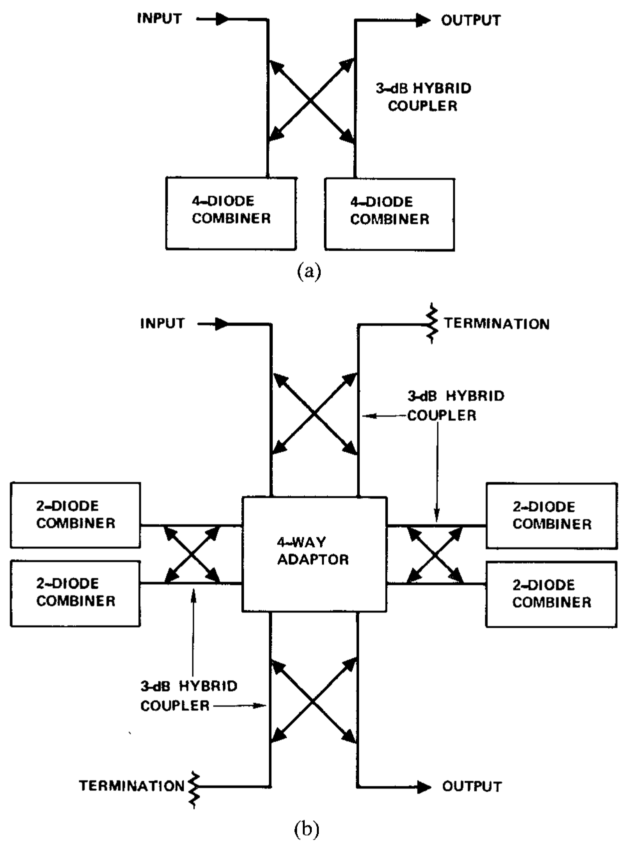

Fig. 1. Hybrid-coupled eight-diode combiner. (a)Hybrid coupling two four-diode combiners. (b)Hybrid coupling four two-diode combiners.

sliding short and Eccosorb loads for the individual diodes. However, as the number of diodes inside the resonant cavity increases, the tuning becomes quite sensitive and harder to control because of a much stronger coupling among the diodes. For the number of diodes greater than four, we found the tuning is practically intractable. In a hybrid-coupled combiner, the insertion loss in the 3-dB short-slot hybrid also poses an upper limit on the number of sources that can be combined [3]. In order to further increase the output power, it is necessary to join different types of combining techniques. For example, an eight-diode combiner can be constructed by combining either two four-diode waveguide cavity combiners or four two-diode waveguide cavity combiners through hybrid couplers. The schematic diagram for these combinations is shown in Fig.

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1, where the waveguide cavity combiners serve as the basic modules for the hybrid-coupled combiner. The overall combiners shown in Fig. 1 can be considered as two-level combiners because they comprise both resonant type (e.g., waveguide cavity combiners) and nonresonant type (e.g, hybrid-coupled combiners) combining schemes. The same concept can be generalized to include other combining schemes such as chip-level power combiners and active phased arrays to form "multiple-level" combiners.

The operating frequencies of the waveguide cavity combiners must be well matched before they can be joined together by hybrid couplers. Since the four-diode waveguide cavity combiner is more difficult to tune to a desired frequency, it is easier to join four two-diode combiners. The disadvantage is a slightly higher insertion loss due to the four-way adapter and the additional hybrid couplers required for this configuration.

III. Two-Diode Combiner Modules

Compatible high-power diodes were first selected to form two-diode combiners, which constituted the basic building blocks for the final stage of the transmitter. The circuit used for the two-diode combiner was modified from that proposed by Kurokawa [4]. The design and performance of such a combiner has been reported previously [2] and will not be repeated here. Typically, peak output power of 20–23 W can be achieved with 80–90-percent combining efficiency. Because of the narrow injection-locking bandwidth, minimum frequency chirp is required for the two-diode combiners before injection locking. This can be done by providing an upward ramp on the bias current pulses. Using this method, frequency chirp of two-diode combiners was reduced to 300 MHz or less. The two-diode modules form the basis for the two-level combiners.

IV. 3-dB Hybrid Coupler and Four-Way Adaptor

The fundamental components in hybrid-coupled combiners are the 3-dB hybrid coupler and four-way adapter. At W-band frequencies, it is imperative to reduce the insertion loss of these components for efficient combining. The hybrid couplers used for this work were of standard design [4]. A disassembled coupler is shown in Fig. 2(a). Both machined and electroformed couplers were evaluated with the latter displaying considerably superior performance.

The hybrid coupler was tuned to operate in a frequency range of 91.5–93.5 GHz since most waveguide cavity combiners oscillated at this frequency range. The insertion loss and isolation among different ports were measured and typical results are shown in Fig. 2(b). As can be seen, the insertion loss was 0.7 dB and the isolation at least 22 dB. This insertion loss also includes the 0.2-dB loss in each of the two adapter arms, therefore, the net insertion loss of the hybrid is only 0.3 dB.

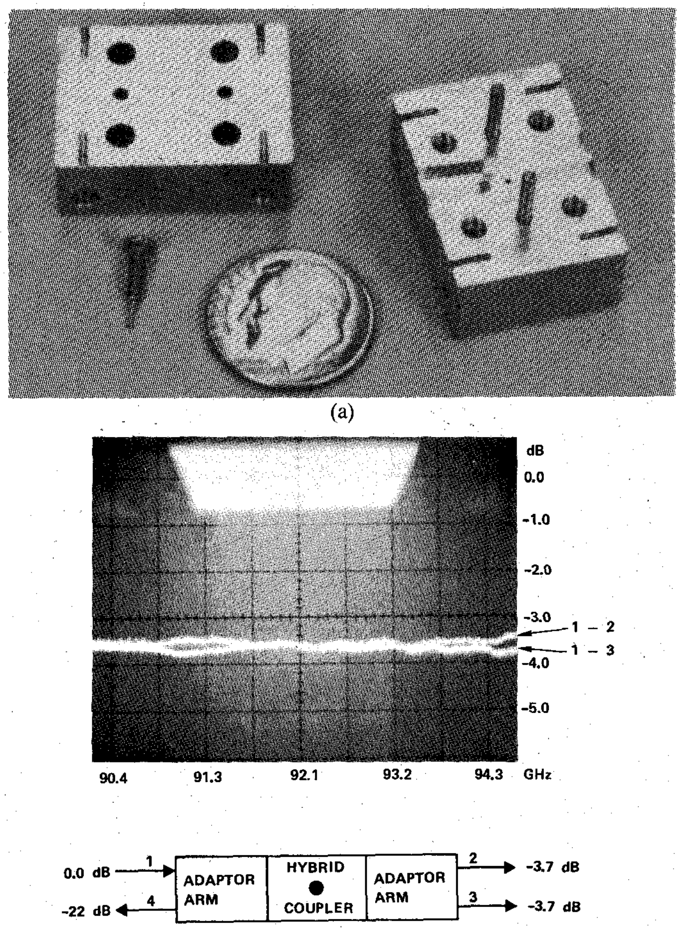

Fig. 2. A W-band 3-dB short-slot hybrid coupler. (a) Disassembled view. (b) Insertion loss measurement.

A four-way adapter was also developed to join four modules through four short-slot hybrid couplers. The adapter was also made by electroforming technique with insertion loss of 0.2 dB per 90° path.

V. Transmitter Using Two Hybrid-Coupled Power Combiner Modules (Four Diodes)

A three-stage transmitter using two hybrid-coupled modules (four diodes) as the final power stage was constructed. The block diagram of this transmitter is shown in Fig. 3 and a photograph of the hybrid-coupled output stage is shown in Fig. 4. The first stage is a low-power CW IMPATT source. It was biased at about 220 mA and had 100-mW output power. Since this power level was insufficient to drive the final output stage, an intermediate stage was added that used a single-diode pulsed IMPATT source with 10-W peak output power. This single-diode pulsed source was injection locked by the CW source to produce a coherent pulse, which in turn injection locked the final high-power stage. Due to limited injection locking bandwidth for a given injection power, the frequency chirping for the source to be injection locked should be kept minimal. This is particularly important for the pulsed sources be-

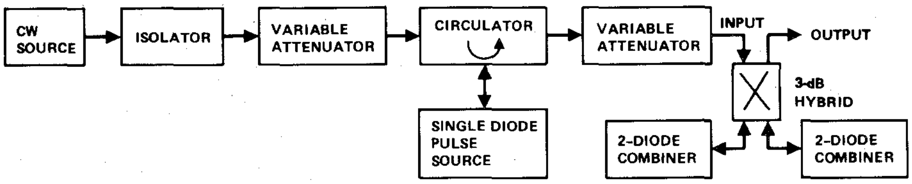

Fig. 3. Block diagram for a three-stage injection-locked transmitter using a four-diode combiner as the final stage.

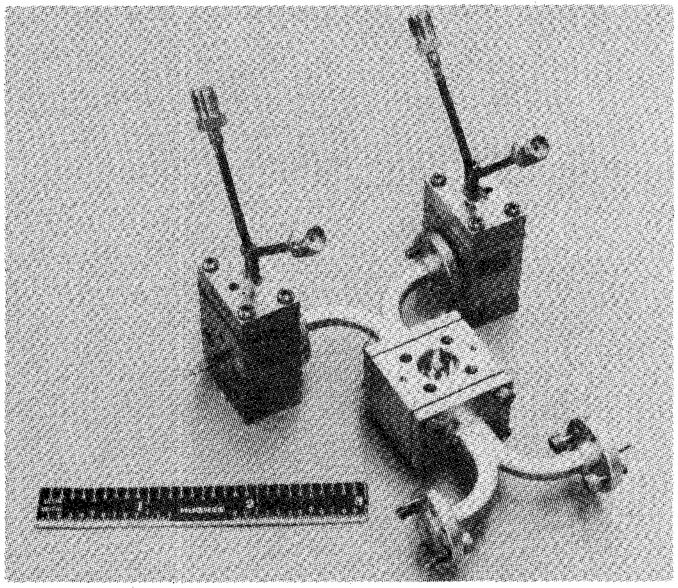

Fig. 4. Hybrid-coupled combiner combining two two-diode waveguide cavity combiners.

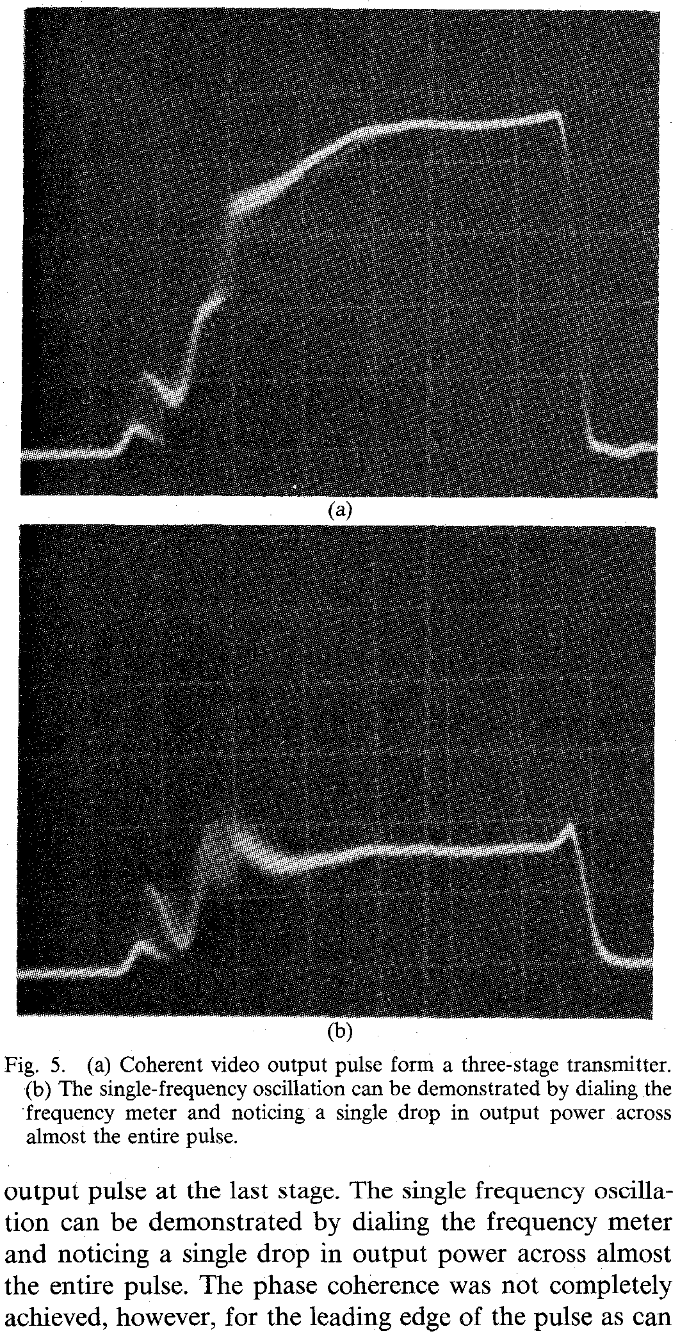

Fig. 5. (a) Coherent video output pulse form a three-stage transmitter. (b) The single-frequency oscillation can be demonstrated by dialing the frequency meter and noticing a single drop in output power across almost the entire pulse.

cause of the temperature-induced chirping during the biasing of the diodes. For pulsed diodes, the frequency chirp can be reduced substantially by upramping the bias current shape. However, residual chirping is always present, especially in the leading portion of the pulse. The frequency chirp of the single-diode pulsed driver was first reduced to 250 MHz before it was injection locked by the CW source. After injection locking, a coherent output with less than 100-MHz chirp over a 100-ns pulsewidth was observed.

The last stage consists of two two-diode combiners hybrid-coupled though a 3-dB short-slot hybrid coupler as shown in Fig. 4. Each combiner produced 23-W output at 92.6 GHz, and each was dechirped to less than 200 MHz. Before the driver signal was applied, the combiner amplifier was biased to a free-running oscillation state. Due to a random starting phase relationship between these two combiner outputs, substantial power was reflected back to the input port, reducing the available power at the output port. As the driving power was increased, the oscillations were gradually synchronized to the injecting signal, resulting in the correct phase relationship and operating frequency required for the proper operation of the power combiner. A coherent peak output power of 40 W with about 250-MHz overall frequency chirp was obtained. The combining efficiency was 85 percent and the loss in the hybrid combining circuit was 0.7 dB. Fig. 5 shows the coherent video output pulse at the last stage. The single frequency oscillation can be demonstrated by dialing the frequency meter and noticing a single drop in output power across almost the entire pulse. The phase coherence was not completely achieved, however, for the leading edge of the pulse as can be seen in Fig. 5. The possible causes for that are qualitatively discussed in Section VI.

One of the important parameters which characterize the injection-locking system is the relationship between the locking bandwidth and the injection-power gain. For a given frequency separation between the locking signal and

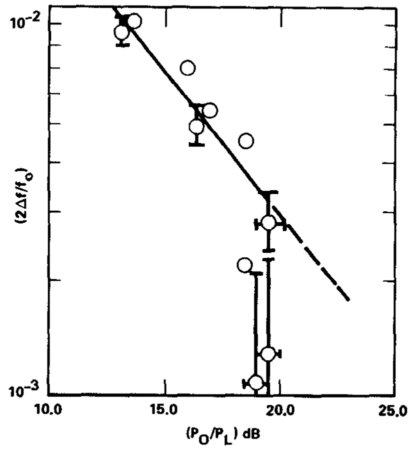

Fig. 6. Fractional injection-locking bandwidth $(2\Delta f/f_0)$ as a function of power gain (P_0/P_L).

the free-running oscillator, the minimum injected power required to pull the oscillator into lock was measured. In practice, the free-running oscillation frequency of the combiner was fixed, while the frequency of the driving CW source was varied. According to the theory, the normalized locking bandwidth $2\Delta f/f_0$ is approximately proportional to $(P_0/P_L)^{-1/2}$ as given by [6]

$$\frac{2\Delta f}{f_0}=\frac{2}{Q_e}\left(\frac{P_0}{P_L}\right)^{-1/2} \tag{2}$$

where f_0 is the free-funning frequency, Δf is the one-sided bandwidth, P_0 is the free-running oscillator power, and P_L is the injection-locking signal power. The proportional constant is related to the external quality factor Q_e of the oscillator circuit. For our transmitter, P_0 is hard to measure directly because of the phase requirement imposed by the 3-dB hybrid coupler, and because all the modules were optimized at 92.6 GHz. For our purpose it was assumed that P_0 is equal to the injection-locked output power, which can be easily measured. Preliminary experimental results indicate that the difference is small. A summary of the experimental results is shown in Fig. 6. The straight line has the slope of -0.5. It can be seen that for larger frequency offset, the data agree reasonably well with the theory, while for small frequency offset, the deviation from the theory is obvious. Most of the errors in this region are due mainly to the lack of frequency resolution of our test setup; relative uncertainty of the locking bandwidth was quite large for small frequency offset. The external Q inferred from these data is about 50, which roughly gives a total locking range of 900 MHz at a locking gain of 13 dB.

It is interesting to note that, for our present transmitter, the injection bandwidths are not quite symmetrical for the frequency offset above and below the free-running frequency. Experimentally, they were found to be 500 MHz and 400 MHz, respectively. It is believed that the combiner amplifier works somewhat better at frequencies above rather than below the free-running frequency. It was also observed that excessive injection power would cause the output signal to degrade, often with a beat frequency reappearing. This beat frequency can be due to the unlocking of the free-running oscillation or due to the presence of spurious oscillations of substantial amplitude. Typically, a 3–5-dB dynamic range for well-behaved injection locking could be obtained. The injection gain for both the pulsed driver amplifier and combiner amplifier could be as high as 20 dB when the driving source frequency and the free-running frequency were very close to each other.

VI. Transmitter Using Four Hybrid-Coupled Modules (Eight Diodes)

In order to further increase the output power, a three-stage transmitter using four hybrid-coupled two-diode combiners (eight diodes) as the final stage was built.

A block diagram of this three-stage transmitter is shown in Fig. 7 and a photograph is shown in Fig. 8. The same CW source and pulsed driver amplifier discussed in the preceding section were used. Two of the four two-diode combiners, each of 23-W peak output power and the other two, each of 18 W were used. The two 23-W combiners were also used in the transmitter discussed previously. All four combiners were tuned to oscillate within 50 MHz of a center frequency of 92.6 GHz and dechirped to less than 300 MHz over a substantial portion of the pulse duration. The transmitter was optimized for maximum power output and high degree of coherence by varying the current bias and relative bias delay for each diode as well as the injection signal levels. Slight tuning of the hybrid couplers was necessary to even out the imbalance among the combiner modules. As shown in Fig. 9, a peak output power of 63 W at 92.6 GHz has been achieved with good coherency. The residual chirping was less than 150 MHz over the last 70-ns pulse duration. The output power variation over that portion was less than 0.5 dB. The combining efficiency was about 76 percent, indicating a 1.2-dB loss in the hybrid-coupled combining circuit.

The initial rising portion of the pulse was only partially coherent, as evidenced by the presence of a noisy kink on the oscilloscope display. The difficulty in achieving a good coherency in the leading edge of the output pulse from multiple combiners is due to the following reasons.

1) The frequency chirp on the leading edge from each combiner output cannot be completely reduced to the extent desired; therefore, these leading potions may not be injection locked with the available injection power.

2) The RF output pulsewidth from each combiner was not the same for all the modules. In general, each combiner output was aligned at the trailing edge. Furthermore, during the process of maximizing the total output power, the bias currents for each diode were delayed by different amounts relative to each other, resulting in a wider time span over which at least one bias was turned on. Therefore, not all the power would combine coherently over the whole pulsewidth. Consequently, the pulsewidth of the injection signal from the driver amplifier stage was not long enough to cover the entire output pulsewidth.

3) The power level of the pulse injection signal was

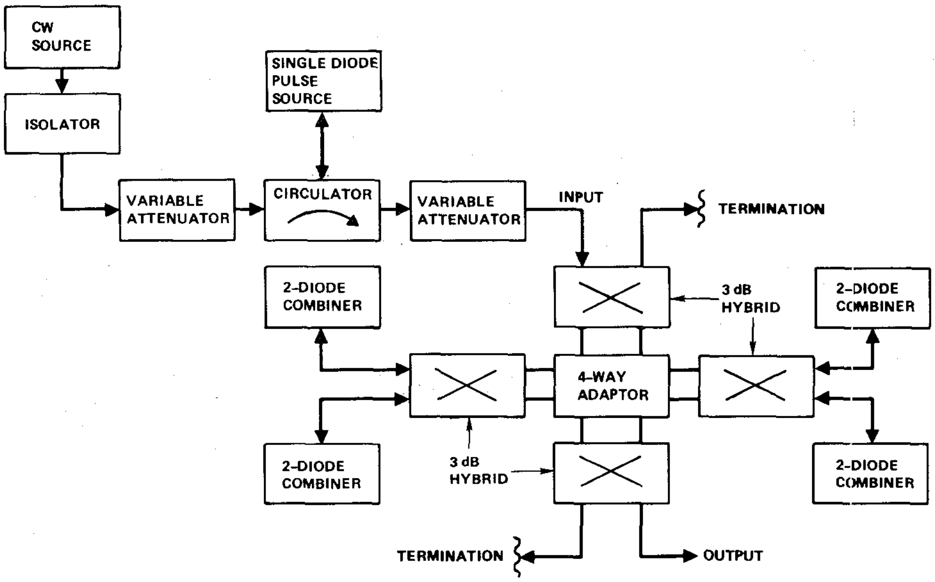

Fig. 7. Block diagram for a three-stage injection-locked transmitter using an eight-diode combiner as the final stage.

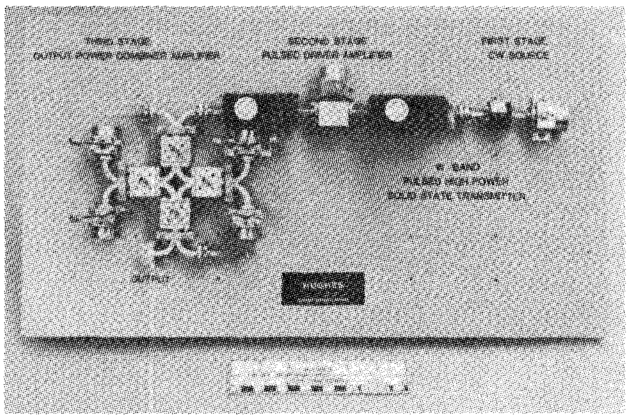

Fig. 8. A 63-W peak output power three-stage injection-locked transmitter.

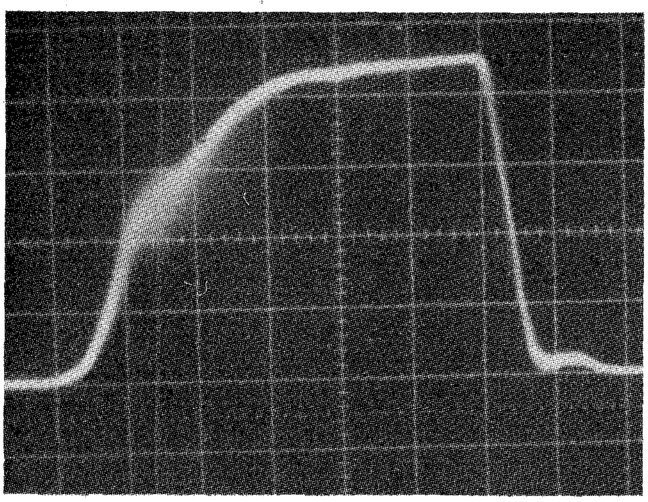

Fig. 9. Transmitter video output pulse. Horizontal scale: 20 ns/div; vertical scale: 50 mV/div.

constant over the width of about 100 ns, which was not sufficient to completely lock the leading portion of the pulse due to a larger frequency spread there.

Most of these contributing factors can be remedied, however, by improvements in the pulse modulator output pulsewidth, bias current shaping, and timing. Nevertheless, these deficiencies also point out the intrinsic problems associated with the coherent power combining of multiple pulsed diodes. For coherent transmitter applications, the scheme of operating the pulsed diodes with pulsewidth somewhat longer than the desired value and using a pair of fast, high-power p-i-n diode switches to gate off the incoherent portion of the leading and trailing edges of the resultant pulse merits further development.

VII. Conclusions

A high-power three-stage injection-locked pulsed transmitter using four hybrid coupled two-diode combiners as the final stage has been developed. Coherent peak output power of 63 W at 92.6 GHz has been achieved. This achievement has firmly established the feasibility of using multiple-level combiners for high-power coherent solid-state transmitters.

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Kai Chang (S'75–M'76), for a photograph and biography please see page 1284 of this issue.

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