Carrier Pulses at Microwave and Millimeter-wave Frequencies

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Summary—**This paper discusses some recent experimental results obtained using special gallium arsenide point-contact diodes for the generation of phase-locked carrier pulses in the microwave and millimeter-wave bands. Several methods of generating such pulses are described. 11.2-Gc microwave phase-locked carrier pulses of about 1.0-nanosecond base duration have been generated at a 160-megabit/second rate. These microwave pulses, which are generated directly from a baseband signal, normally have peak power levels in excess of 0.5 mw. Millimeter-wave phase-locked carrier pulses have also been generated at 56 Gc. These very high frequency pulses have a base duration as short as 0.25 nanosecond and occur at a 160-megabit/second rate. Furthermore, phase-locked carrier pulses have been generated at frequencies as high as 89.6 Gc. A simple method of generating nonphase-locked 0.3-nanosecond millimeter-wave carrier pulses directly from 1.92 gigabit/second rate baseband pulses has also been investigated. The experimental arrangement used to demonstrate the "turn on" and "turn off" principle of transient carrier pulse generation is described.**

I. Introduction

MICROWAVE phase-locked carrier pulses have been generated by p-n junction charge-storage diodes directly in waveguide from baseband signals as reported previously [1]. The carrier pulses were generated in this instance from the recovery transient at the end of conduction ("turn off"). From the experimental results obtained at that time it was found that carrier pulses could be generated from the recovery transient at useful repetition rates up to 1000 megabits/second.

The work reported in this paper is a continuation of work carried on earlier at the Crawford Hill Laboratory. Much of the previous work has been described in the references given at the end of this paper. Concerned readers should consult the appropriate reference papers for more detailed background material [1]–[11].

The present paper discusses some more recent experimental results using gallium arsenide point-contact diodes to generate both microwave and millimeter-wave phase-locked carrier pulses in waveguide from a transient generated at the start of conduction ("turn on"). The input signals used to generate these carrier pulses from the "turn on" transient were either UHF sine waves in the range between 500 and 1000 Mc or fractional nanosecond pulses. Experimental results obtained using gallium arsenide point-contact diodes for direct amplitude modulation of a millimeter-wave CW carrier are also discussed.

The technique we have used for generating short pulses is based on employing an ultra short pulse or impulse (infinite rise and fall) generator which can be included in a suitable wide-band coupling network. In this paper when the coupling network has a low-pass characteristic the resulting pulses are termed baseband pulses. When the coupling network has a band-pass characteristic the pulses are termed band-pass or carrier pulses. For the base-band case the output of the coupling network is in coaxial, stripline or other types of low-pass transmission line, while for the band-pass or carrier case the output of the coupling network can be either coaxial, stripline or waveguide.

For the case of an impulse generator, the actual bandwidth of the network filters employed in both the baseband and band-pass circuits would determine the duration of the output pulse. For the low-pass case we have used coupling networks having over-all responses of the order of 10 Gc. For the band-pass or carrier case, the maximum bandwidth possible will be dependent on the chosen center frequency which would be the nominal carrier frequency of the desired output pulse. In order to avoid excessive delay distortion without using delay equalization, the bandwidth obtainable is normally about 20 per cent. At 56 Gc we were able to use the 10 Gc bandpass associated with the TWT.

It is well known that the Fourier harmonics of a repetitive impulse are phase-locked to the phase of the fundamental frequency and if there are no band limitations the amplitude of the harmonics are all equal. When a coupling network or filter is used to shape the baseband or carrier pulses, the frequency characteristic of the network determines the shape or envelope of the pulses. Satisfactory pulses can only be produced by this method with a linear phase characteristic, or when the delay distortion is negligible.

For convenience this paper is divided into sections. Section II discusses the experimental arrangement used in demonstrating the "turn off" and "turn on" diode operations. Section III discusses, in three parts, the generation of microwave and millimeter-wave carrier pulses. Section III-A discusses the generation of phase-locked microwave and millimeter-wave carrier pulses from baseband signals by means of one-step harmonic generation. Section III-B discusses the generation of phase-locked millimeter-wave carrier pulses from base-

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band signals by two steps of harmonic generation. Section III-C discusses the generation of nonphase-locked millimeter-wave carrier pulses by simple conventional amplitude modulation. Included within Sections III-A, B and C are oscillograms obtained using both the band-pass stroboscope [1] and the baseband electrical stroboscope [2].

II. Generation of Phase-Locked Carrier Pulses by Means of a "Turn-On" or "Turn-Off" Transient

Previous experience with *p-n* junction charge-storage diodes showed that ultra-short pulses could be generated from the sharp step produced by the "turn off" of diode conduction. Baseband pulses in a coaxial diode mount and phase-locked carrier pulses in a waveguide diode mount were generated using this "turn off" effect. On the other hand, early work with the gallium arsenide point-contact diodes suggested that the carrier pulses obtained resulted from a different mechanism, later identified as resulting from the "turn on" of conduction in these diodes.

A simple experiment was devised to observe the relation between the time of generation of the carrier pulses and the "turn on" or "turn off" of the conduction of the particular diode under test. By using a variable-length test pulse it is possible to determine whether the carrier pulse is generated by the "turn on" or "turn off" of diode conduction. For example if the carrier pulse moves in time *only* when the leading edge of the test pulse is moved, the carrier pulse is generated by the "turn on" of conduction. If the carrier pulse moves in time *only* when the trailing edge of the test pulse is moved, the carrier pulse is generated from the "turn off" of conduction.

Two variable length test pulses were used for the experiment described above. One was a simulated pulse consisting of two fractional nanosecond pulses with a 0.5-nanosecond spacing between pulse peaks. The other simulated pulse made use of two 10.0-nanosecond pulses with a 5-nanosecond spacing. (See Fig. 1 for reference.) With these test pulses, the leading edge or the trailing edge could be moved with respect to a reference time by simply removing either the first or second pulse. Fig. 2 shows a simple block schematic of the experimental arrangement which includes a strobe-frequency carrier pulse generator which produced phase-locked carrier pulses at the strobe frequency. As shown in Fig. 2, a 3-db combining coupler is introduced so that band-pass strobe techniques can be used to view the phase-locked carrier pulses on a low-frequency oscilloscope. In this band-pass stroboscope application, only the carrier frequency signal and strobe harmonics transmitted through the waveguide, and the following traveling wave tube are combined in the baseband demodulator.

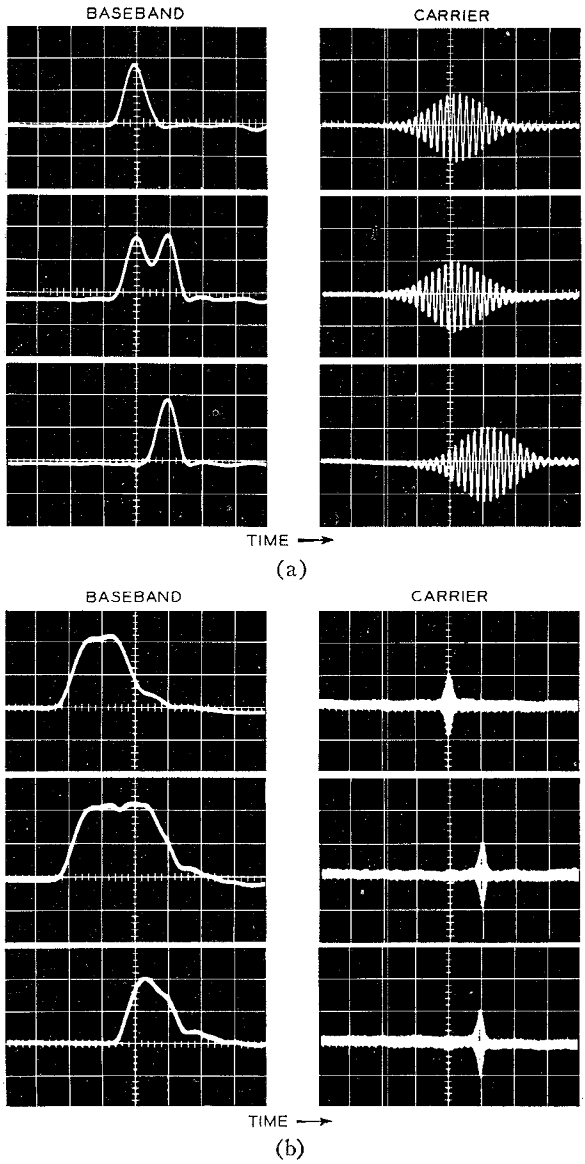

Fig. 1—Waveforms of baseband and phase-locked carrier pulses. (a) Point contact gallium arsenide. 11.2-Gc pulses generated from "turn on" (horizontal 0.5 nanosecond/division). (b) *p-n* junction silicon. 11.2-Gc pulses generated from "turn off" (horizontal 5 nanosecond/division).

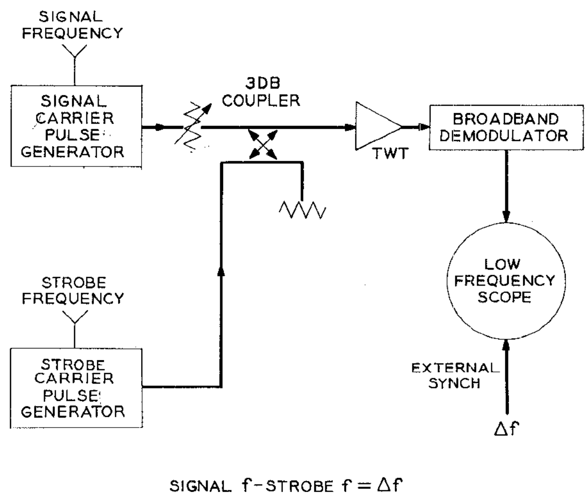

Fig. 2—Block diagram of experimental setup for generation and viewing phase-locked carrier pulses produced in one step of harmonic generation.

The output of the demodulator contains the difference frequency harmonics which form the low-frequency replica of the microwave carrier pulse. In this particular case both signal and strobe carrier pulses are limited to a 2-Gc band centered at 11 Gc. This limits the pulse resolution to slightly more than 1 nanosecond. Oscilloscope synchronization is obtained from an externally generated 100-cycle wave which is the difference frequency between the basic crystal controlled signal and strobe oscillators. This provides an accurate time reference.

Listed below are the normal pulse outputs observed when the two variable length pulses mentioned above were used to generate carrier pulses.

1) *Gallium Arsenide Point-Contact Diodes*

a) No carrier pulse is generated from the 10-nanosecond slow rise and fall driving pulses.

b) Carrier pulses are generated from the 0.5-nanosecond sharp rise and fall pulses. An extremely fast transient is generated by these diodes when driven into conduction by a steep wavefront ("turn on").

2) *Silicon p-n Junction Diodes*

a) Carrier pulses are generated from the recovery transient at the end of conduction ("turn off") when 10-nanosecond slow rise and fall pulses are used to drive the diode.

b) "Turn off" carrier pulses are not generated from the 0.5-nanosecond sharp rise and fall pulses. The short duration of the pulse does not allow sufficient charge to be stored during the conduction cycle.

The output pulses observed for both types of diodes, driven as explained above, are as shown in Fig. 1. The character of the driving baseband pulse is shown on the left. The resulting carrier pulse pictures appear on the right. Fig. 1(a) shows the pulse pattern obtained for a typical point-contact gallium arsenide diode. For this diode it is seen that a *rise* time "turn on" coincidence rule is followed. The resulting carrier pattern does not move in time when the driving pulse trailing edge is moved. However, when the leading edge is moved, the carrier pattern does shift in time to coincide with the shift in *rise* time of the baseband driving pulse.

Fig. 1(b) shows a similar set of oscillograms for a typical *p-n* junction-type silicon diode. In this case, however, the carrier patterns are seen to be in time coincidence with the *fall* time of the driving baseband pulses, the carrier pulses being generated at the time of the diode "turn off." Thus, a shift in time of the trailing edge of the driving pulse causes a shift in the time position of the carrier pattern while a change in time of the leading edge results in no shift in the carrier position.

III. Generation of Microwave and Millimeter-Wave Carrier Pulses

A. Generation of Microwave and Millimeter-Wave Phase-Locked Carrier Pulses by One Step of Harmonic Generation

The generation of microwave phase-locked carrier pulses from baseband signals by one step of harmonic generation was briefly discussed in Section II. The experimental results using gallium arsenide point-contact diodes show that the carrier pulses in this case are generated from a "turn on" transient when the waveguide mounted diodes are driven with sharp rise time, short duration baseband signals.

Using the microwave waveguide mounting arrangement shown on Fig. 3, 11.2-Gc carrier pulses having a peak power in excess of 0.5 mw were generated at a 160-megabit/second rate. The 0.5-nanosecond duration, 160-megabit/second rate baseband signal is applied to the diode through the coaxial low capacity broad-band choke shown toward the top of Fig. 3. The diode is mounted across the center of the wide dimension of RG 52/U waveguide. The lower supporting post for the diode is insulated and by-passed to ground by means of a suitable condenser. This provides a means of applying external bias and of monitoring diode current. The RF output of the diode contains all the generated harmonics of the baseband signal above the 6.56-Gc cutoff frequency of the waveguide. In one case where this device was being used to generate 11.2-Gc pulses, a 32-db conversion loss for peak power was recorded.

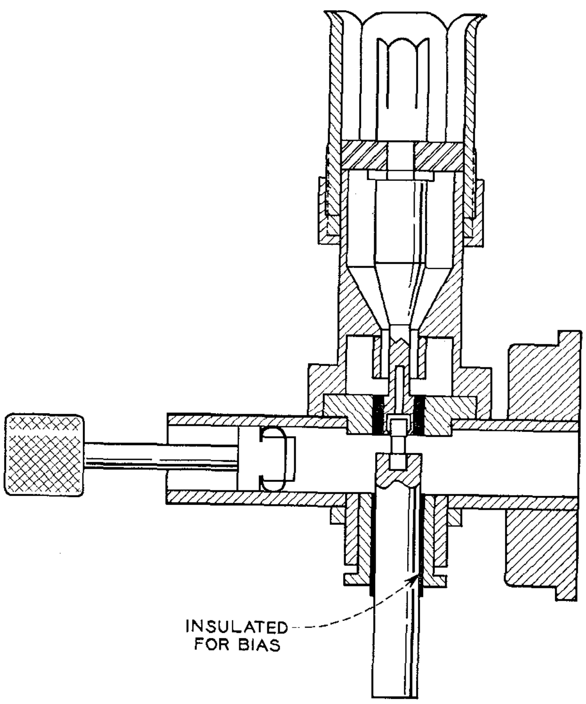

Fig. 3—Cross-sectional view of *X*-band waveguide mount.

Fig. 4(a) shows an enlarged cross-sectional view of the special point-contact cartridge unit employed in the above experiments. The unit is similar in appearance to one previously described in a published paper by Sharpless [4]. These units used in our pulse experiments, however, use different point-contact springs and are formed at higher current levels. The semiconductor material is *n*-type single crystal gallium arsenide having a low resistivity of 0.002 ohm-cm. The small *S*-spring point is made of one-mil tungsten wire for strength, and the contact tip is copper plated to supply the doping needed during the forming operation. It is believed that a small amount of copper (a *P*-type doping agent in gallium arsenide) diffused into the *N*-type gallium arsenide during the forming, produces the abrupt junction desired.

In practice the 11.2-Gc carrier pulses generated with these diodes are amplified with a suitable traveling wave tube. Fig. 5(a) shows the amplified waveform of a 160-megabit/second phase-locked carrier pulse observed with a bandpass electrical stroboscope [1]. In this picture the horizontal sensitivity of the oscilloscope is 0.25-nanosecond/division, and one can see that there are somewhat more than 11-RF cycles contained in a 1.0-nanosecond period which are actual cycles of the 11.2-Gc carrier frequency. The envelope duration is slightly more than 1.0 nanosecond.

56.0-Gc phase-locked carrier pulses have also been generated by one-step harmonic generation in the millimeter waveguide. In this case 0.5-nanosecond duration, 160 megabit/second rate baseband pulses are used to drive gallium arsenide wafer diode units similar to the unit shown in Fig. 4(b). The over-all block diagram of this experiment is the same as shown on Fig. 2. Band-pass stroboscope techniques were again used. The two millimeter wave outputs are combined at the proper levels in a 3-db directional coupler and amplified by a millimeter-wave traveling-wave tube. The TWT in this case provides approximately a 6-db bandwidth of 10 Gc, centered at 56 Gc [5].

At the top center and on the right of Fig. 6 are shown the two low-capacity output wafer-type millimeter wave rectifier holders and diodes [6] used as the harmonic generators for the above test. Also shown are the level setting signal branch attenuator, and the 3-db directional coupler employed.

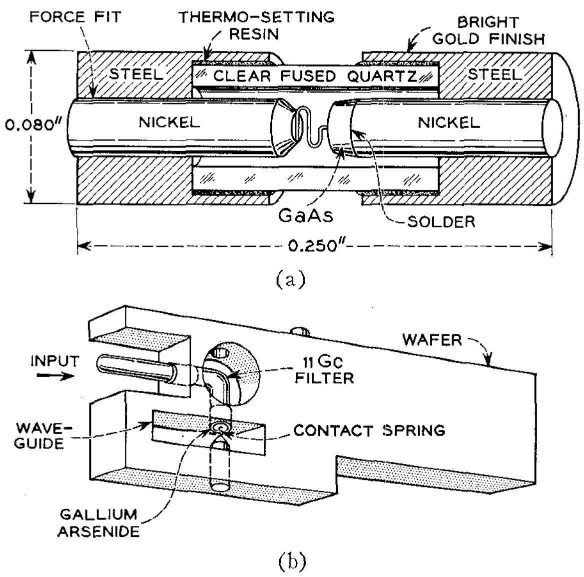

Fig. 4—Gallium arsenide diode assemblies. (a) Cartridge unit. (b) Millimeter-wave wafer unit.

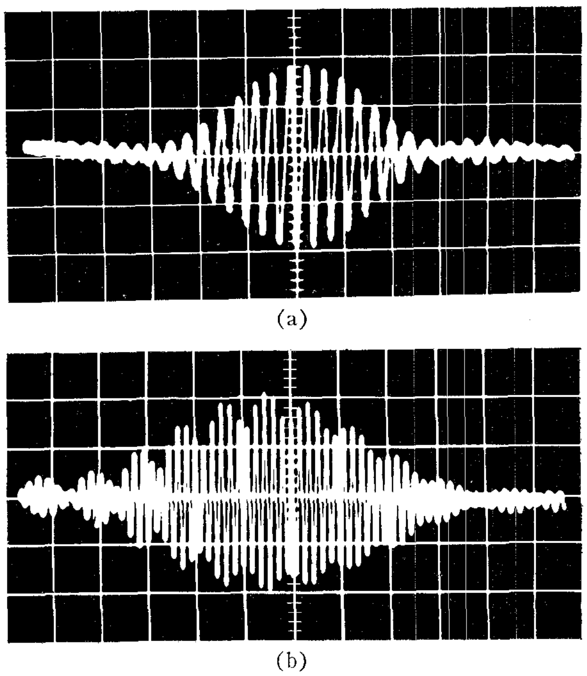

Fig. 5—Waveforms of phase-locked carrier pulses obtained with band-pass electrical stroboscope. (a) 160-megabit/second rate, 11.2-Gc pulses (horizontal 0.25 nanosecond/division. (b) 160-megabit/second rate, 56-Gc pulses (horizontal 0.1 nanosecond/division).

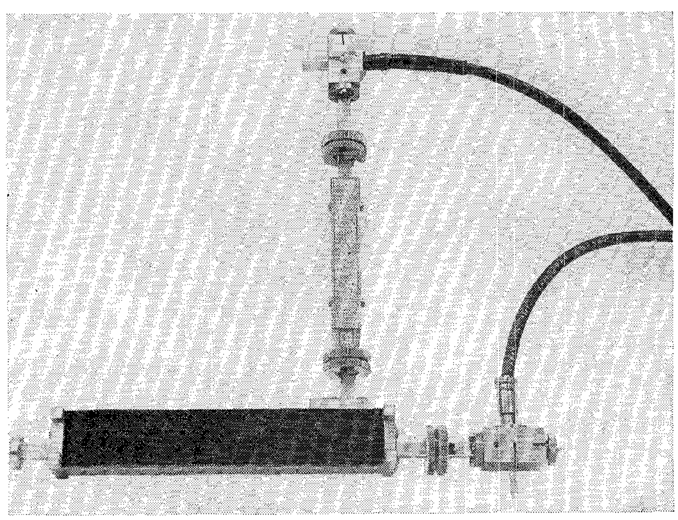

Fig. 6—Photograph of baseband to millimeter-wave band (50–60 Gc) harmonic generator units and associated components.

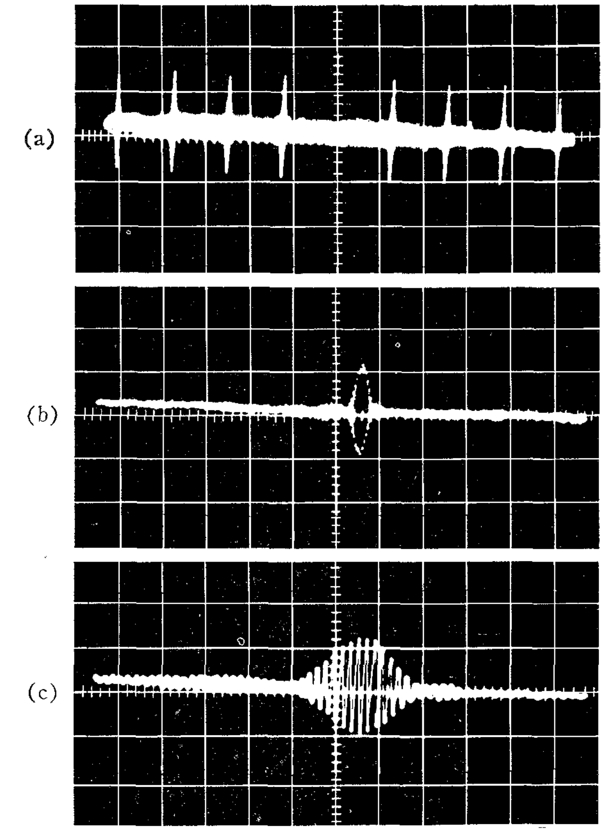

Fig. 7—Waveforms of directly generated, 160 megabit/second rate, 56-Gc phase-locked carrier pulses obtained with band-pass stroboscope. (a) Horizontal 5.0 nanosecond/division. (b) Horizontal 0.5 nanosecond/division. (c) Horizontal 0.1 nanosecond/division.

Fig. 7 shows stroboscopic oscillograms of the millimeter wave pulses obtained at a frequency of 56 Gc. Fig. 7(a) shows a series of 160-megabit/second rate carrier pulses with the horizontal sensitivity of the oscilloscope set at 5.0 nanoseconds per division. Fig. 7(b) shows a single carrier pulse when the expansion has been increased by a factor of ten (0.5 nanosecond/division). Fig. 7(c) shows the individual phase-locked millimeter-wave RF cycles within the pulse envelope. The expansion has been further increased to 0.1 nanosecond /division for this picture. While the observed pulses have an envelope duration of 0.25 nanosecond, it is felt that the generated pulses are considerably shorter, being primarily limited in this case by the 10-Gc band of the millimeter-wave traveling-wave tube.

B. Generation of Phase-Locked Millimeter-Wave Carrier Pulses by Two-Step Harmonic Generation

A second stage of harmonic generation with a multiplication of 5 times may be used to produce phase-locked 56-Gc carrier pulses from the 11.2-Gc pulses previously described [7]. The millimeter wafer unit used for this purpose also makes use of a gallium arsenide point-contact diode. Fig. 4(b) shows this wafer unit diode in some detail. This unit is similar in appearance to a wafer unit described earlier [6]. The semiconductor material employed for this unit is single crystal gallium arsenide having a resistivity of about 0.03 ohm-cm. One mil diameter, copper-plated tungsten spring points of the same type used in the 11-Gc cartridge units are also employed in these wafer units. For this application, the built-in by-pass condenser arrangement normally used as the low-frequency output circuit has been redesigned to form a π network input filter tuned to 11.0 Gc. Fig. 8 shows the complete harmonic generator assembly with part of the wafer unit just described shown extending from the top of the assembly. The previously amplified 11.2-Gc pulses are introduced at the RG 52/U input port. In the holder these pulses are impressed on the wafer unit diode which in turn generates the 56-Gc output pulses. The output is taken from the side of the holder in RG 98/U waveguide. A connection is provided so that the dc crystal current can be monitored and an external bias applied as desired. The unit is so designed that both the resistive and reactive components of the diode impedance can be matched to the waveguide. In this case the available 11.2-Gc peak pulse driving power was 200 mw. With the drive on and the diode adjusted for an average rectified dc current of about 3 ma, the peak pulse output power obtained, at 56.0 Gc, was in the range of 2 to 4 mw. Fig. 5(b) shows a picture of the waveform of the phase-locked 56-Gc carrier pulse obtained using the band-pass electrical stroboscope arrangement shown in Fig. 9. The pulse repetititon rate in this case is 160 Mc and the horizontal sensitivity is 100 picoseconds/division. The spacing between the RF cycles is therefore as shown approximately 18 picoseconds at the 56.0-Gc carrier frequency.

The microwave pulse generators in Fig. 9 are the same microwave units as shown on Fig. 3. The microwave signal applied to the top branch consists of 160-megabit pulses of 0.5-nanosecond duration. A gallium arsenide crystal is used in the signal branch. The strobe pulse generator uses a FD 100 charge storage diode. The strobe frequency wave applied to the second microwave pulse generator consists of a high amplitude 160-Mc sine wave. In general, it should be noted that the strobe frequency is less than the signal frequency and in this particular case the 160-Mc strobe frequency was 800 cycles less than the 160-Mc signal frequency. The signals from the two millimeter wave harmonic generators are combined at the proper level in a 3-db coupler and applied as shown to the broad-band demodulator. The demodulator output, which is a strobed down low-frequency replica of the millimeter-wave carrier pulse, is applied to a low-frequency oscilloscope. Synchronization for the sweep of this oscilloscope is obtained by taking the difference between the basic signal and strobe frequencies in a separate synchronizing circuit.

More recently, in a physical arrangement the same as shown in Fig. 9, by employing special RG 138/U waveguide components, it was found possible to generate phase-locked carrier pulses up to 89.6 Gc. The equipment used for this experiment is shown in the photograph of Fig. 10. Previously amplified 11.2-Gc

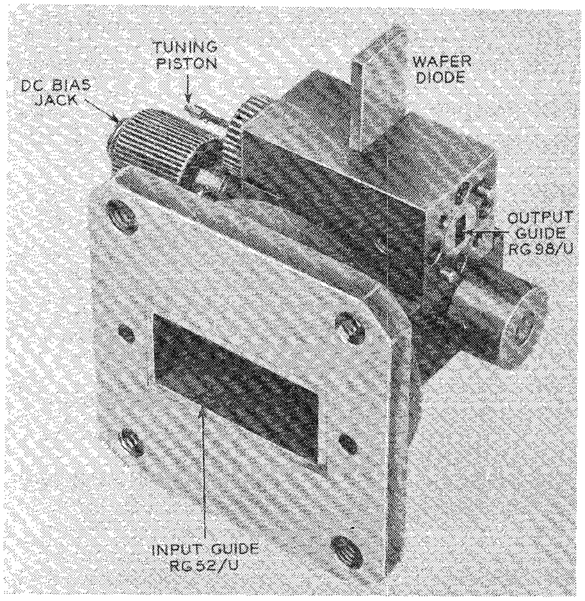

Fig. 8—Photograph of X-band to millimeter-wave band harmonic generator unit.

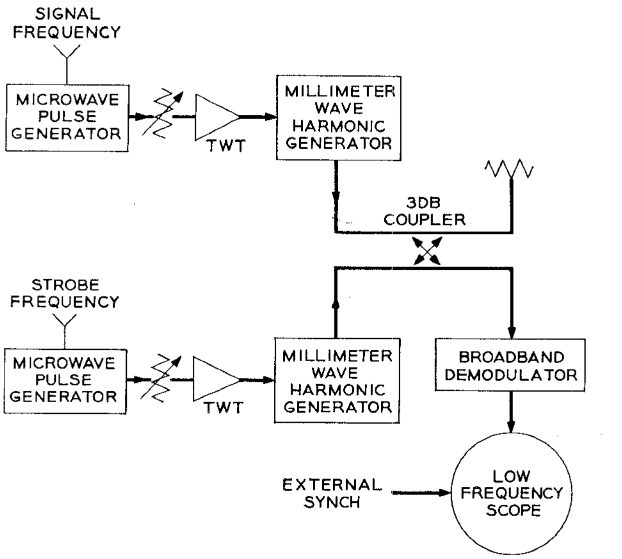

Fig. 9—Block diagram of experimental setup for generating and viewing phase-locked carrier pulses produced in two steps of harmonic generation.

signal and strobe pulses are separately introduced into the two RG 52/U input ports as shown on the lower portion of the photograph. In this case the eighth harmonic of each input is generated in the two RG 138/U point-contact GaAs wafer diodes shown mounted in their holders on the left sides of the two 11-Gc guides. The harmonics generated by these diodes are fed through short sections of RG 138/U waveguide and are combined by means of a miniature finline coupler [8]. The output of this coupler is fed directly to a tuned point-contact wafer type demodulator diode and the final output is displayed on a scope. The wafer diodes used in this experiment are of a new design and are intended for operation in the frequency range between 90 and 140 Gc [9]. The harmonic generator diodes employed N-type gallium arsenide as a semiconductor

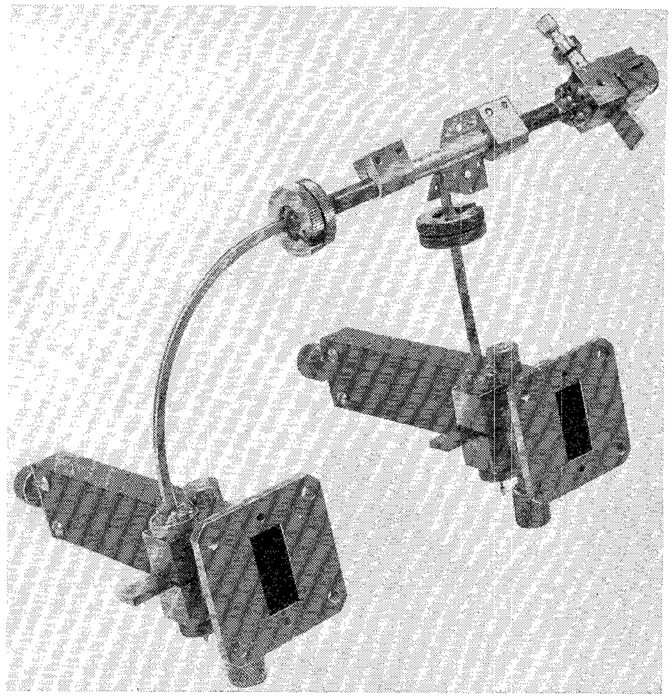

Fig. 10—Photograph of X-band to millimeter-wave band (90–130-Gc) harmonic generator units, finline coupler and broadband demodulator.

material, while the demodulator-detector diodes are processed using either P-type aluminum doped silicon or heavily doped N-type germanium. When these germanium diodes are used as final detectors, they are best operated in the backward direction [10].

C. Generation of Millimeter-Wave Carrier Pulses by Amplitude Modulation

So far this paper has dealt with the generation of phase-locked carrier pulses by harmonic generation. The generation of fractional nanosecond 56-Gc RF or carrier pulses by direct amplitude modulation of a 56-Gc CW carrier with 0.3-nanosecond duration, 1.92 gigabit/second repetition rate baseband clock pulses in a reflection modulator will now be discussed. The oscillograms for this section were obtained using the baseband stroboscope [2] after envelope detection of the modulated millimeter-wave pulses. Therefore, in this case the RF carrier was not phase locked to the phase of the fundamental baseband frequency. The reflection modulator consists of a modulating diode in a suitable broad-band mount. The gallium arsenide diode wafer unit used in this modulator is of the the same type used in the harmonic generator previously described in Section II-B.

Fig. 11 shows the block diagram of the equipment used for the direct pulse amplitude modulation experiments. In practice the CW signal is applied to the input arm of the 3-db directional coupler and the diode is adjusted for a good match. When the baseband modulating signal is added, the diode no longer matches the waveguide and a carrier pulse with the envelope duration of the baseband pulse is reflected to the output port. The RF pulse is amplified by a millimeter-wave

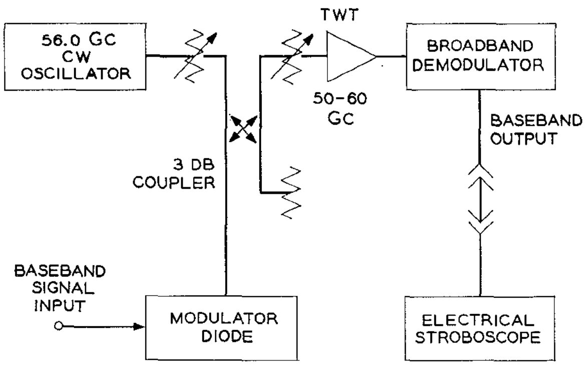

Fig. 11—Block diagram of experimental setup for generating 56 Gc, 1.92 gigabit/second rate carrier pulses.

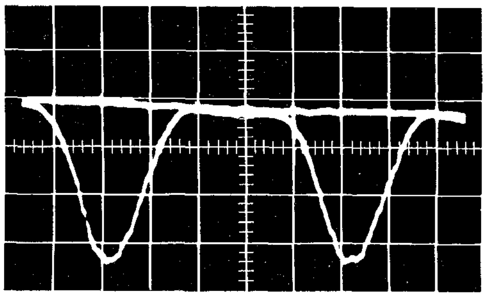

Fig. 12—Waveform of detected 1.92 gigabit/second rate 56-Gc carrier frequency clock pulses obtained with the baseband electrical stroboscope (horizontal 0.1 nanosecond/division; vertical 3.0 milliwatts/division).

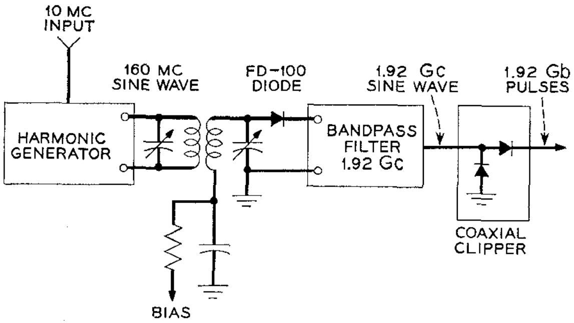

Fig. 13—Block diagram of experimental setup used for generating the 1.92 gigabit/second rate clock pulses.

traveling-wave tube and is applied to a broad-band demodulator. The detected output is observed on the baseband electrical stroboscope.

Fig. 12 shows the waveform of the recovered envelope of the 1.92-gigabit/second clock pulses. The input-carrier is gated so that a zero carrier reference is available for evaluating the CW-carrier leakage through the modulator. In this case the modulating pulses are produced from 160 Mc in the following manner. Harmonic generation from a 160-Mc sine wave to a 1.92-Gc sine wave is accomplished using a *p-n* junction charge-storage diode [3]. The sharp step waveform, containing harmonics of 160 Mc is generated from the recovery transient and is applied to a 1.92-Gc (12th harmonic) three cavity narrow-band filter. The sine wave output is clipped with gallium arsenide point-contact diodes used as series and shunt clippers, to produce the 0.3-nanosecond pulses of 1-volt peak amplitude. The block diagram of this arrangement is shown on Fig. 13.

Conclusions

This paper has reported our continuing work in the field of generation and measurement of ultra-short carrier pulses. Oscillograms obtained using our band-pass electrical stroboscope show that phase-locked band-limited 0.25-nanosecond base duration pulses have been obtained at 56 Gc with a 10-Gc band-pass system.

It appears that the "turn on" effect using the special waveguide mounted gallium arsenide point-contact diodes as described in this paper could be used to generate even shorter pulses, provided wider bandwidth waveguide systems are devised.

References

[1] A. F. Dietrich, "8 and 11-Gc Nanosecond Carrier Pulses Produced by Harmonic Generation," Proc. IRE, (*Correspondence*) vol. 49, pp. 972–973; May, 1961.

[2] W. M. Goodall and A. F. Dietrich, "Fractional millimicrosecond electrical stroboscope," Proc. IRE, vol. 48, pp. 1591–1594; September, 1960. See also W. M. Goodall, U. S. Patent No. 3,009,105; November 14, 1961

[3] A. F. Dietrich and W. M. Goodall, "Solid state generator for 2×10^{-10} second pulses," Proc. IRE (*Correspondence*), vol. 48, pp. 791–792; April, 1960.

[4] W. M. Sharpless, "High-frequency gallium arsenide point-contact rectifiers," *Bell Sys. Tech. J.*, vol. 38, pp. 259–270; January, 1959.

[5] H. L. McDowell, W. E. Danielson, and E. D. Reed, "A half-watt CW traveling-wave amplifier for the 5–6 millimeter band," Proc. IRE, vol. 48, pp. 321–328; March, 1960.

[6] W. M. Sharpless, "Wafer-type millimeter wave rectifiers," *Bell. Sys. Tech. J.*, vol. 35, pp. 1385–1402; November, 1956.

[7] An application of this technique is given by A. F. Dietrich, "Simple millimeter wave frequency standard," *Rev. Sci. Instr.*, vol. 33, pp. 486–487; April, 1962.

[8] These millimeter wave finline couplers are a miniature version of a device described earlier by S. D. Robertson, "Recent advances in finline circuits," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 263–267; October, 1956.

[9] W. M. Sharpless, "Point-contact wafer diodes for use in the 90–140 kilomegacycle frequency range," *Bell Sys. Tech. J.*, vol. 42, pp. 2496–2499; September, 1963.

[10] C. A. Burrus, "Backward diodes for low-level millimeter-wave detection," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-11, pp. 357–362; September, 1963.

[11] S. E. Miller, "Millimeter waves in communication," *BPI, Proc. Symp. on Millimeter Waves*, Polytechnic Press, Polytechnic Inst. of Brooklyn, N. Y., vol. 9, pp. 25–43; 1959.