OPTICAL GENERATION AND CONTROL OF MICROWAVES AND MILLIMETER-WAVES

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ABSTRACT

I report the generation and control of microwaves and millimeter-waves by optoelectronic techniques. Complete time synchronization between microwave and optical signals is achieved. RF waveform generations, ranging from one single cycle to continuous wave with peak power up to a few kilowatts, have been demonstrated. Laser controlled phase shifters, switches and modulators at 94 GHz are described. The state-of-the-art in the general area of microwave optical interactions is reviewed.

INTRODUCTION

Rapid advances in both microwave and optical technologies make is possible to integrate them together to form a new class of devices that can perform high speed/high frequency electronic functions. With the advent of femtosecond lasers (10 femtoseconds optical pulses have been generated) we envision such devices to work in the picosecond time domain. We refer to this new technology as picosecond optical electronics, which combines the fields of optics and electronics. The link for these two fields is picosecond photoconductivity.

The ideas of using photoconductivity effect for the control of microwave solid state devices have been of great interest to the microwave community recently. For example, optical control of IMPATT,(1-3) TRAPATT(4), MESFET(15-6), transferred-electron devices(7) and HEMT(8) has been reported. Microwave signal generation at 35 GHz by optical mixing of injection locked laser diode sources(9) and indirect optical injection locking of a free-running 39 GHz IMPATT oscillator(10) have been demonstrated. The basic operation principle of all these devices is the photogeneration of free electron-hole pairs within the active region of the device. Photoexcited carriers modulate transconductance and other circuit parameters (such as gate-source and drain-gate capacitances) of the Devices. Therefore optical illumination will either enhance or quench the oscillation of these devices.

Optical Technique for controlling the microwave devices offers unique advantages in: (1) near perfect isolation between controlling and controlled devices, (2) elimination of RF feed in a large array system, (3) immunity from electromagnetic interference, (4) light weight and compact size, (5) extremely fast response, (6) high power handling capability, and (7) possiblility for monolithic integration. In the references mentioned above, the extreme high speed capability of the lightwave technologies has not been exploited. Very recently, the high speed aspect of the picosecond optical pulse technique has been utilized for microwave measurements of GaAs IC using electrooptic sampling (11).

In our laboratory, we have taken advantage of the unique speed capability of the optical pulses. Electrical pulses are instantaneously generated via picosecond photoconductivity (12) effect in a photoconductor. Picosecond photoconductor can now be engineered to generate electric pulse as short as 1 ps(13) with jitter free switching. All subsequent electronic events are slaved to this initial pulse. Picosecond optical technique can be utilized again to generate other pulses that can be precisely time controlled. Using picosecond optical electronic technique, we are able to generate microwave and millimeter-wave signals that are in complete time synchronization with the exciting optical pulses. RF waveform generations, ranging from one monocycle to continuous wave with peak power up to a few kilowatts, have been achieved. Phase control of the microwave signals can be accomplished by simply controling the arrival time of the exciting optical pulses.

PICOSECOND PHOTOCONDUCTOR

A photoconductor exhibit picosecond response time is referred to as a picosecond photoconductor. This phenomena is referred to as picosecond photoconductivity effect which was first reported in 1972(14). Picosecond photocnductors used as ultrafast switching and gating devices were demonstrated in 1975(15). In this application, the photoconductor is dc biased at the input terminal and a fast rised electrical output signal is obtained instantaneously when it is irradiated by a picosecond optical pulse. Thus in a sense, it is a three terminal device where the control terminal is an optical port.

There are a large number of devices based on the picosecond photoconductivity effect. They include switches, gates, sampliers, electronic impulse function correlators, A/D converters, optical detectors, DC to RF converters and coherent microwave generators. All these devices

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- jitter free switching;
- ultrafast risetime, usually the risetime of the optical pulse;
- ultrafast falltime when materials with picosecond carrier lifetime are used;
- high power handling capability;
- scalable to large size or submicron size;
- large dynamic range;
- capability of being operated near the intrinsic breakdown field of the material;
- possibility for monolithic integration with microelectronic devices.

Based on these features, many applications may follow. They are:

(1) high data rate optical signal processing;
(2) master clock;
(3) high speed switching, sampling, gating, and modulating;
(4) high speed, broadband optical detector;
(5) streak camera triggering;
(6) ultrashort, high power, high voltage pulse generation;
(7) optical control of millimeter-wave propagation, millimeter-wave phase shifting, modulating, switching, and gating;
(8) coherent microwave and millimeter-wave generation;
(9) electromagnetic pulse protection (EMP) or nuclear electromagnetic pulse protection (NEMP);
(10) repetitively opening switches for inductive energy storage system;
(11) hot carrier transport study;
(12) on-chip picosecond diagnostics for VHSIC or HEMT devices involving picosecond electrical pulse generation and detection and VHSIC device characterization.

In this talk, I will concentrate on the discussion of experments related to microwave applications only.

GENERATION OF KILOWATT BROADBAND COHERENT MICROWAVE BURSTS

Using a picosecond optoelectronic switching technique, we can generate multiple cycle RF waveforms with amplitude in the kilovott range. The electric impulse generated by an optoelectronic switch is coupled to a coaxial structured resonating cavity. This impulse will then bounce back and forth on the coaxial line resulting in a series of pulses with alternating polarities. An output coupling element is used to extract these pulses out. A damped periodic pulse train of microwave radiation is obtained. Using this technique, RF radiations ranging from 300 MHz to 1.5 GHz were obtained. The number of RF cycles could be controlled to vary from as few as one cycle to several hundreds of cycles. The peak amphitude for the microwave pulses up to 1.25 kilovolts and peak power of 8 kilowatts were obtained[16].

SEQUENTIAL WAVEFORM GENERATION BY USING SEVERAL OPTOELECTRONIC SWITCHES IN A FROZEN WAVE GENERATOR

A frozen wave generator consists of a group of charged line segments connecting by photoconductive switches. By closing the switches simultaneously, this device can generate sequential waveforms. To use frozen wave generator to produce high voltage elctrical waveform it is essential that the photoconductive switches have high transfer efficiency and zero jitter time when closing. In addition the switches should also withold high voltage. Using equal length transmission line segments, we are able to generate two and one-half cycle RF waveform with kilovolt amplitude. By changing the bias voltage to each segment and varying the length of the segments, we can also generate various asymmetrical, stair-steps, aperiodic waveforms, etc. These devices obviously have applications in radar.

A NEW OPTOELECTRONIC CW MICROWAVE SOURCE

The precise generation and control of microwave and millimeter-wave signals using integrated technology is essential for the next generation of high-speed, broadband systems. It is desirable to utilize optoelectronic components where possible for such applications as microwave and millimeter-wave signal processing, receivers/transmitters and phased array antennas. We now have at our disposal optoelectronic devices that work in the picosecond time domain. The trend is toward a class of devices which integrate optics into electronic functions.

We have demostrated earlier the generation of 3 GHz CW signals by the pulse excitation of a resonant cavity. the generation of short pulses of microwave signals has been reported [15]. Also, a 3 GHz CW signal has been generated by using a mode-locked krypton ion laser with both an avalanche photodiode and an optoelectronic switch [17]. In (18), a technique involving the FM sideband injection locking of a laser diode has been used to generate a 35 GHz CW signal. This was done by beating two longitudinal modes of a diode laser in a high speed PIN detector. This technique requires accurate temperature stabilization of the lasers and provides a signal level of -53 dBm.

This paper will elaborate on the realization of a 10 GHz CW microwave source using the photoconductivity effect. An advantage of this technique is that the components required are relatively easy to obtain and use. The technique requires a minimum number of components: a source of short optical pulses (a mode-locked laser), a picosecond optical switch, a microwave filter, and an amplifier. Each of these components have the flexibility of being reduced in size so that the entire configuration may be integrated onto a single substrate. This will minimize the detrimental effects of dispersion, connectors, and cables, enhancing the overall performance. The output power and stability of the signal generated by this technique are the most critical factors in determining its applicability. The noise performance of the source is of particular importance and has not previously been considered in detail for this application. Methods for increasing the power level and reducing the amplitude and time fluctuations in the output signal will be discussed.

The method for generating CW electrical signal consists of converting a periodic optical pulse train at 100 MHz repetition rate to an electrical pulse train. Since the risetime of the electrical pulses is 3 picoseconds, the spectral components of the electrical pulses extend up to hundreds of gigahertz and are spaced every 100 MHz. Any component can be isolated by appropriate filtering and subsequent amplification. We are able to generate 10 GHz at -30 dbm in this manor. Recent results in our laboratory indicate that signal at 20 GHz can also be obtained readily.

The 10 GHz signal generated by this technique must satisfy general stability requirements so that it may be used in the applications discussed above. Extensive measurements have been made to calculate the frequency stability of the CW signal generated. The rms timing jitter of the 10 GHz signal produced in our experiment is approximately 3.53 ps. This number has been computed by the RF spectrum method from the sideband phase noise power between 30 Hz and 5KHz. Methods of improving both the AM noise fluctuations and the rms timing jitter have been discussed. It is presently assumed that the jitter contributed by the switch is extremely small. Stabilization of the YAG laser using a phased locked loop my be necessary for more comprehensive noise evaluations and certain application. The overall jitter can be reduced to less than 0.3 picoseconds[11].

ULTRAFAST OPTOELECTRONIC MODULATION AND PHASE CONTROL OF 94 GHz MILLIMETER- WAVES

To realize an electronically controllable phase array system in the millimeter-wave region, one requires a large number of switches and phase shifters which can be operated with high speed (~ one nanosecond) and with a time precision of several picoseconds. Such kinds of phase shifters, switches, and modulators are currently not available, yet there is a great need to develop these types of devices. In this paper, we present the results of theoretical and experimental studies of a new class of devices in which the propagation parameters of the millimeter-wave signals are controlled by a laser induced electron-hole plasma in a semiconductor waveguide. It is well known that the complex dielectric constant of a semiconducting medium can be modified by the introduction of an optically induced electron-hole plasma.

Shown in Fig. 1 is a schematic of the optically controllable millimeter-wave device. It consists of a rectangular semiconductor waveguide with tapered ends to allow efficient transition of millimeter-waves both to and from a conventional metallic waveguide. Optical control is realized when the broad wall of the semiconductor waveguide is illuminated by picosecond laser pulses.

We have successfully demonstrated the concept of optically controlled millimeter wave devices. Millimeter-wave phase shifters at 94 GHz have been constructed. A millimeter-wave brigde was employed[19]. This experimental arrayement is shown in Fig. 2. Initially, without laser illumination of the semiconductor waveguide, the bridge was balanced by adjusting the variable attenuator A and the mechnaical phase shifter ϕ in arm b so that there was no signal at the output. When a single .53μm pulse from a frequency doubled mode-locked Nd:YAG laser illuminated the semiconductor waveguide, a high-density electron-hole plasma was generated at the surface, causing phase shift and attenuation of the millimeter-wave signal as it propagated through the plasma covered region of the waveguide. The bridge became unbalanced and a signal appeared at the output. This signal persisted until the excess carriers recombined. Phase shifts of 300^{o}/cm were observed from a Si waveguide with a cross-section of 2.4 x 1.0 mm^2 and 1400^{o}/cm from a GaAs waveguide with a cross-section of 2.4 x 0.5 mm^2. These values are in good agreement with theoretical predictions. By using a fast photoconductor as the semiconductor waveguide, it is possible to switch out a short millimeter-wave pulse. 94 GHz pulse with duration of 400 ps has been obtained. Rapid modulation of the 94 GHz is also possible. We have achieved modulation rate of 250 MHz with modulation bandwidth in access of 1 GHz.

It has been shown that a plasma generated throughout the bulk will create large loss. A surface plasma, however, merely changes the boundary conditions. It is suspected that an optically-controlled phase shifter utilizing this fact will yield large phase shifts with low attenuation. the specific waveguide examined in this paper is Silicon-on-Sapphire and Silicon-on-Alumina. Experimental result shows that indeed with initial high density, the loss is small than its maximum value which occurs at a later time when the density becomes low.

CONCLUSION

We have shown several picosecond optoelectronic devices that can control the generation and modulation of the RF waves ranging from low frequency up to 94 GHz. Phased array system locked to the optical pusle is feasible with this technique. This work was supported in part by the Army Research Office, National Science Foundation, Air Force Office of Scienctific Research and the Laboratory for Physical Sciences.

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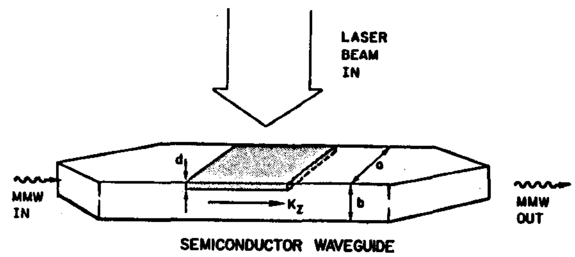

Fig. 1 Optically control millimeter waveguide.

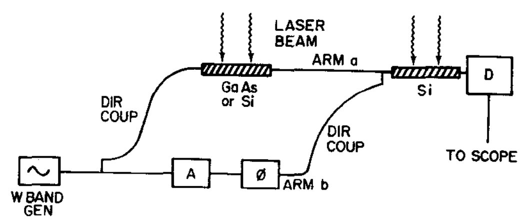

Fig. 2 Experimental arrangement.