Optical Control of Microwave Semiconductor Devices

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(Invited Paper)

Abstract —The use of optical signals to control the operation of microwave amplifiers, oscillators, switches, and mixers is reviewed. Among the active devices treated are Gunn and IMPATT oscillators, MESFET and HEMT amplifiers, oscillators, and mixers, and diode mixers. Future directions for research in this area are discussed.

I. Introduction

DIRECT optical control of microwave semiconductor devices has been an area of growing interest since the beginning of the last decade. Various RF control functions including gain control of amplifiers, oscillator tuning, locking and frequency modulation, switching, mixing, limiting, and phase shifting have already been demonstrated [1], [2]. A valuable recent review article [3] cites some 120 studies, which by no means represent all of the recent publications in this area.

Optical techniques have attracted interest largely because of their very wide bandwidth, the inherent high dc and reverse signal isolation between the control and RF signals, and their suitability for use with optical fiber links. Rapid advances in laser diode technology, particularly the increase in available modulation bandwidth and the possibility of integrating the optically controlled devices in microwave monolithic integrated circuit (MMIC) or optoelectronic integrated circuit (OEIC) forms, have simulated further interest in optical control techniques. Optical control of microwave semiconductor devices has already been used in active phased array radars and is likely to find application in RF, microwave, and wide-band signal processing systems.

Most applications of optical signal distribution in microwave systems have used photodetectors for the recovery of the optical modulation [4]. This paper reviews an approach that will be of importance in future systems: the use of optical signals to control or introduce signals directly into microwave devices. There are several attractions to this approach. First, no extra electronic circuits are required to process the detected signals before application to the microwave device; nor are any circuit parasitics, which may limit response speed, introduced. Second, optical control introduces an extra control port to devices that are difficult to control electrically, such as avalanche devices. Third, the optical control signal is immune to electromagnetic disturbances, such as EMP.

The basic process in direct optical control of microwave semiconductor devices is the photoexcitation of carriers (hole–electron pairs) within the active region of the device when light with photon energy greater than the band gap of the semiconductor is absorbed. In a p–n or Schottky junction depletion region, the main effect is to generate a photocurrent and to change the built-in potential of the junction, which modifies the dimensions of the depletion region and gives a small effective forward bias in the same manner as the operation of a solar cell. Elsewhere, the photoconductive effect increases the conductivity of the semiconductor material. Therefore, the absorption of light changes both the resistive and the reactive behavior of the devices, the response time being governed by carrier dynamics.

Optoelectronic switching and gating devices are also of interest, owing to their picosecond precision, simplicity of operation, and the inherently high isolation they offer between electrical and optical signals. However, they will not be considered further here since a good recent review is available [5].

In this paper we review the use of optically controlled devices to perform a range of circuit functions. The paper is organized as follows. In Section II the optical control of amplifier performance is discussed. Section III treats the optical control of both two- and three-terminal oscillators while Section IV discusses optically pumped mixers. Finally Section V draws conclusions from the work reviewed and suggests areas for further development.

II. Optically Controlled Amplifiers

Optical control of microwave amplifiers can be achieved in two different ways: (i) by direct injection of light into the device active region or (ii) by indirect means, such as

Manuscript received September 7, 1989; revised December 8, 1989. This work was supported in part by the U K. Science and Engineering Research Council and by Telebrás (Telecommunicações Brasileiras S.A.)

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IEEE Log Number 8934034.

0018-9480/90/0500-0577$01.00

using a photodetector to convert the optical energy to electrical energy, which then acts to change the gain of the device. Several authors have studied the direct control of microwave amplifiers using three-terminal devices such as GaAs MESFET's [6]–[10] and HEMT's [9], [10]. Also, indirect gain control of a GaAs MMIC distributed amplifier, by controlling its biasing circuit, has been reported recently [11]. Indirect control will not be considered further here, since the amplifier gain control mechanism is electrical. The direct injection of light into the device active region is in principle an efficient process and may offer some benefits such as large dynamic range and wide bandwidth. Also, the illumination of GaAs MESFET amplifiers can improve both linearity and intermodulation distortion [12].

A. Optical Control of FET Amplifiers

The basic mechanism arising in optical illumination of the MESFET is the production of free carriers (hole–electron pairs) within the semiconductor material when light of photon energy equal to or greater than the semiconductor band-gap energy is absorbed. In Fig. 1 the schematic geometry of the GaAs MESFET is shown. Gaps between source and gate and between gate and drain allow penetration of light, which is absorbed in the active region and in the substrate. Photovoltaic effects in the gate Schottky barrier region and in the active channel to substrate barrier occur, as well as photoconductive effects in the parasitic resistances in series with the active channel and in the substrate. These change the relevant parameters of the device, such as the transconductance, the gate-to-source capacitance, the channel resistance, and the source series resistance. By correctly designing the input and output matching circuits, the change in these parameters can be used to provide a desired modification of the MESFET terminal characteristics. Theoretical and experimental results [6]–[10] have shown that under appropriate conditions, the dominant effect in the control of the gain is due to the change of the S_{21} parameter, resulting from the change in the transconductance of the device with illumination. The basic mechanism for the change in the transconductance is due to a combination of the photovoltaic effect in the gate Schottky barrier and photoconductive effects in the parasitic resistances in series with the MESFET active channel. The photovoltaic effect in the gate Schottky barrier is very dependent on the gate bias resistance value. When a low resistance is connected to the gate bias circuit, the photovoltage developed across the gate junction is small and the transconductance varies very little. Hence, a small gain control range (around 2–3 dB) is obtained with illumination [8]–[10]. However, a high photovoltage (~ 0.4 V) is developed across the gate junction when a high external resistance (> 50 kΩ) is connected to the gate bias circuit. Then the photovoltage developed is superimposed on the reverse gate bias and the overall effect is that under illumination, the gate depletion region is "pinned" to a forward bias near the open-circuit photovoltage of the Schottky barrier. Hence, by using very small optical power (a few microwatts), up to 20 dB of change in the gain can be obtained when the bias gate voltage is chosen close to the pinch-off voltage [7]. Then, without illumination the device provides a high isolation (≥10 dB), and under illumination the gain is around 10 dB. The rate at which the gain can be changed is basically limited to the time constant of the input circuit. For typical values of gate-to-source capacitance (~ 0.5 pF) and for a gate bias circuit resistance of 100 kΩ, $\tau \sim 50$ ns, which may be adequate in many applications.

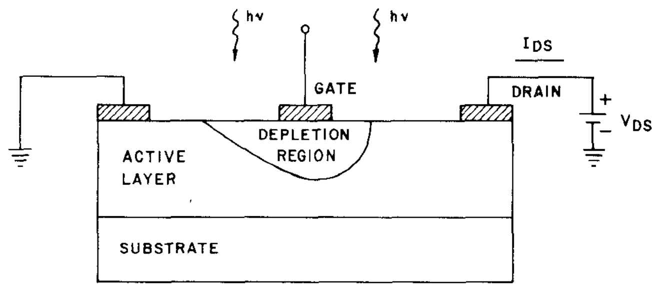

Fig 1. Schematic diagram of the GaAs MESFET under illumination.

B. Optical Control of HEMT Amplifiers

HEMT's are very attractive devices for integration with other MMIC or OEIC components on a single semi-insulating GaAs or InP substrate. Also, the optical absorption coefficient and the energy band gap can be tailored to a particular wavelength by adjusting the mole fraction of the constituent materials. Optical control of HEMT amplifiers was reported in [9] and [10]. The experiments reported show that at a center frequency of 13.25 GHz the increase in the magnitude of S_{21} with illumination can be up to 2 dB for a gate bias voltage of around −1 V. Further theoretical and experimental work for the HEMT amplifier under illumination may improve its performance.

It is important to note that experiments have shown that the phase of S_{21} in MESFET's and HEMT's is insensitive to optical illumination [7]–[10]. The optical sensitivity of MESFET's is of the order of 0.5 A/W [13]. An analytical study taking into consideration material properties in HEMT's shows that these devices have a higher sensitivity to optical illumination, and experimental results with GaAlAs/GaAs HEMT's have shown optical sensitivities of the order of 3.5 A/W [10] and 4.2 A/W [14]. Given the small amount of optical power needed, simple and inexpensive optical sources (such as LED's) can be used to control the gain of FET and HEMT amplifiers.

III. Optically Controlled Oscillators

Three main forms of oscillator control are possible and are illustrated in Fig. 2. Control can be achieved either directly, where the optical control signal illuminates the oscillator active device, or indirectly, where the control signal illuminates an ancillary device forming part of the oscillator resonant circuit [15]. The latter technique will not be considered further here.

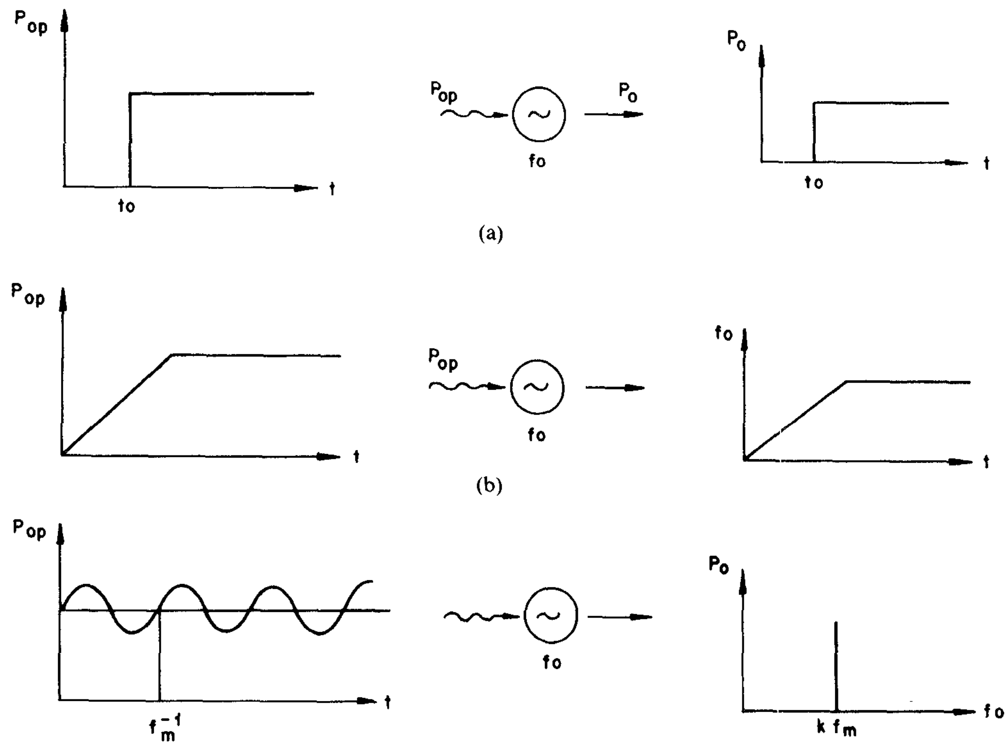

Fig. 2. Optical control of oscillators: (a) optical switching, (b) optical tuning, (c) optical injection locking.

In optical switching (Fig. 2(a)) a change in the intensity of the optical control signal leads to a change in oscillator output power. Optical frequency tuning (Fig. 2(b)) is also achieved by varying the incident optical intensity; however the intensity levels used are generally much lower than for optical switching. In optical injection locking (Fig. 2(c)) the optical control signal is intensity modulated at a frequency close to the free-running frequency of the oscillator ($k=1$, fundamental locking), one of its harmonics (k integral, harmonic locking), or one of its subharmonics (k fractional, subharmonic locking). This modulated optical signal absorbed in the device active region gives rise to current flow at the modulating frequency in the device, and this acts in a very similar way to direct microwave signal injection as described by Adler [16] and Kurokawa [17].

The above phenomena have been demonstrated for a variety of oscillator devices.

A. Gunn Diode Oscillators

The Gunn diode was the first microwave semiconductor device to be optically controlled. Optical tuning of UHF Gunn oscillators has been studied by several authors [18]–[20] with a tuning range of a few percent of the center frequency. Significant power variations were also observed and in one study [20] it was found that some devices would not oscillate unless illuminated. Long time constants (>100 ns) were also found to be associated with the optically induced frequency shifts in some devices [19]. It seems likely that a major cause of the observed effects was the emptying of trap levels in impure material by the incident light, which would account for the wide variation in results between individual devices.

More recently Carruthers *et al.* have studied the use of picosecond-length optical pulses to trigger short bursts of microwave oscillation from Gunn structures [21]. There remains scope for studies of the optical control performance of Gunn devices fabricated from the high-quality material available with modern epitaxial growth techniques. A theoretical framework for the analysis of optically controlled Gunn devices is yet to be developed.

B. Avalanche Oscillators

The IMPATT diode oscillator remains one of the most powerful solid-state sources at the higher microwave frequencies [22]. However, the power and impedance levels involved make tuning by conventional means, such as YIG spheres or varactor diodes, very difficult. Optical control offers a convenient "third terminal" for the control of the device.

1) Theory: The mechanism of optical control in avalanche devices is that illumination varies the level of reverse saturation current, which alters the rate of avalanche charge buildup and hence the phasing and magnitude of the induced current in the oscillator circuit. By making the simplifying assumptions of equal ionization rates for holes and electrons and carrier motion at saturated velocity, simple expressions for the optical tuning and injection locking ranges can be derived [23]:

$$\frac{d(\Delta\omega)}{dI_{s0}} = \frac{F_a\{X\}}{QI_{dc}\tau_a} \tag{1}$$

and

$$\frac{2\Delta\omega_L}{I_{s1}} = 5F_b\{X\}\frac{I_0\{X\}\,\omega_0}{\pi I_1\{X\}\,QI_{dc}} \tag{2}$$

where $\Delta\omega$ is the change in the free-running oscillator frequency due to optically generated reverse saturation current I_{s0}, $\Delta\omega_L$ is the half locking range for peak modulated optically generated locking current I_{s1}, ω_0 is the free-running oscillator frequency, Q is the oscillator circuit Q factor, and I_{dc} is the oscillator bias current. $I_n\{X\}$ are modified Bessel functions of order n and argument X. The dimensionless parameter X is proportional to the oscillator voltage swing. $F_a\{X\}$ and $F_b\{X\}$ are avalanche gain coefficients representing the effect of avalanche multiplication on the optically generated carriers.

For a typical, uniformly doped IMPATT with 20% voltage modulation $F_a\{X\} = 78$ and $F_b\{X\} = 209$ so that avalanche gain enhances the optical control sensitivity considerably. This is a particular attraction of avalanche devices for optical control. An estimate of optical tuning and injection locking ranges can be obtained on substituting typical oscillator parameters in (1) and (2). For a uniformly doped, single drift silicon IMPATT having $\tau_a = 0.2\pi/\omega_0$ operating in an oscillator circuit of Q factor 100 and frequency 40 GHz, with a bias current of 60 mA and 20% voltage modulation,

$$\frac{d(\Delta f)}{dI_{s0}} = 830 \text{ MHz mA}^{-1}$$

and

$$\frac{2\Delta f_L}{I_{s1}} = 2.53 \text{ GHz mA}^{-1}.$$

If the optical control signal were supplied by a GaAs/GaAlAs laser emitting at 850 nm, giving a maximum possible responsivity of 0.68 A/W, control ranges of hundreds of MHz could be achieved with under 1 mW optical power, given efficient coupling of the control signal to the IMPATT device.

The restrictions involved in an analytic theory can be removed by constructing a large-signal, time-domain computer model of the IMPATT oscillator [23], [24]. Fig. 3 shows optical tuning results from such a model for a uniformly doped W-band single drift silicon device. Two different illumination configurations are modeled. In one electrons are injected into the depletion region from the p^+ region while in the other holes are injected into the depletion region from the n^+ region. These represent illumination from the p^+ and the n^+ region, respectively, with light of wavelength having a high absorption coefficient. The tuning slope for electron injection is seen to be much higher than for hole injection due to the higher avalanche ionization coefficient for electrons in silicon. For purposes of comparison the slope predicted by the analytic theory of the previous subsection is also shown.

2) Experimental Results: Tuning and power variation effects in an illuminated IMPATT oscillator were first reported by Vyas *et al.* [25] and on/off switching of a GaAs IMPATT was reported by Yen *et al.* [26]. In a later paper [27] Vyas *et al.* demonstrated the dependence of oscillator tuning range on photocurrent composition, as discussed in the previous subsection. More recent work has extended optical tuning to frequencies in W-band [28]. The optical tuning sensitivity observed was a factor of 40 less than that shown in Fig. 3. This is a consequence of the different Q factors of the modeled and experimental oscillator circuits.

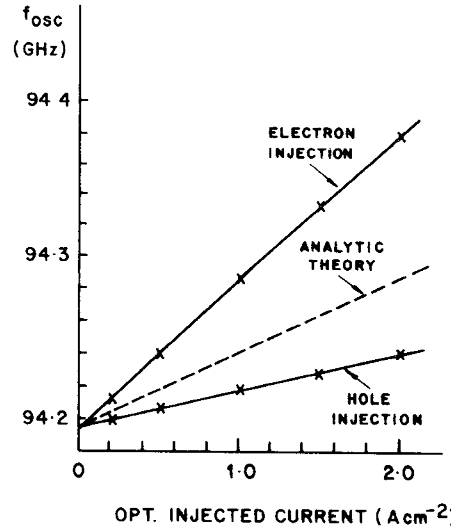

Fig. 3. Comparison between computer model and analytic theory for optical tuning characteristics of W-band oscillator (single drift silicon IMPATT; bias current density 28.45 kA/cm^2).

Optical injection locking of an IMPATT oscillator was first reported by Seeds and Forrest [29] using a directly modulated semiconductor laser as a subharmonic injection locking source. The optical tuning and injection locking ranges reported have all been small, typically less than 1% of the free-running oscillator frequency. This is a result of inefficient coupling of the control signal to the IMPATT. Attempts have been made [27], [23] to fabricate special IMPATT structures of improved responsivity but the combination of efficient optical coupling with the exacting current density and thermal resistance requirements of the device has not proved easy and remains a fruitful area for further work.

3) TRAPATT Devices: Kiehl [30] carried out pioneering work on the optical control of TRAPATT oscillators. However the critical circuit requirements for reliable TRAPATT oscillator operation have led to a decline in interest in this device for systems applications.

C. Three-Terminal Oscillators

Several investigators have demonstrated optical control of three-terminal oscillators using different devices such as silicon bipolar transistors [31], GaAs MESFET's [32]–[36], [9], [10] and GaAlAs/GaAs HEMT's [9], [10]. The main effects observed were (i) optical tuning and frequency modulation, (ii) optical switching, and (iii) optical injection locking. Switching, tuning, and frequency modulation arise from the change of the S parameters of the device with illumination. In a fixed microwave circuit, therefore, the oscillation condition will be satisfied at different frequencies and output levels for different optical illumination intensities.

1) Optical Tuning and Frequency Modulation: Direct optical tuning of three-terminal oscillators in different configurations occurs mainly due to significant changes in the input capacitance of the device with illumination. Given a knowledge of the variation of the device S parameters with illumination, conventional circuit design techniques can be used to optimize tuning bandwidths (as well as output power). Several hundred megahertz of tuning range was obtained in X-band MESFET oscillators for a few microwatts of absorbed optical power from a low-cost LED [33]. Experimental results comparing common-source and common-drain mode GaAs MESFET oscillators have demonstrated that the common-source oscillator has a much higher optical-frequency sensitivity than that of the common-drain configuration. Typical frequency changes with illumination were in the range 100–180 MHz for the common-source configuration and 530 MHz for the common-drain configuration when the oscillation frequency (for both configurations) was in the range 4–8 GHz [35]. In a source series feedback configuration, when the gate-to-source capacitance has a dominant effect in the tuning of the oscillator, a tuning range of around 1 GHz was measured in an X-band GaAs MESFET oscillator, the optical absorbed power being a few hundred nanowatts [7]. A reasonably flat output power (~ 5 dBm± 0.5 dB) was measured within ~ 500 MHz. Also, observations of the spectrum showed that in some cases the FM noise performance of the FET oscillator can be significantly improved with illumination. An important advantage of this technique is that tuning control involves no physical connection to the oscillator circuit; therefore the need for the dc isolation and biasing components associated with varactors is eliminated. Problems of RF rectification and circuit loading by the varactor are also avoided.

Optical frequency modulation of MESFET oscillators was first described in [36], where a 10.2 GHz GaAs MESFET oscillator has shown a modulation frequency bandwidth of around 5 MHz. Ways to improve this frequency bandwidth may include optimization of the gate bias resistance.

2) Optical Switching of Three-Terminal Microwave Oscillators: Optical switching of semiconductor oscillators can be achieved either by an illumination-induced shift of the operating point relative to the oscillation threshold or by optical quenching of oscillations. The rate at which the on and off condition can be changed is very dependent on the device structure and circuit impedances. Switching of silicon bipolar transistor was described in [31]. There, unmodulated optical illumination was equivalent to additional base bias current, and the transistor bias voltage was adjusted slightly below the threshold of oscillation without illumination, so that it would oscillate only when illuminated.

Due to the high sensitivity of the FET and HEMT parameters to optical illumination [7], [9], optically switched oscillators can also be successfully designed using these devices.

3) Optical Injection Locking: Optical injection locking of microwave transistors can occur due to photoexcitation of carriers at the fundamental modulation frequency (or its harmonics or subharmonics) in different regions of the devices. Optical injection locking of silicon bipolar transistors operating at frequencies up to 1.8 GHz was reported in [31]. Optical injection locking at the fundamental frequency and its subharmonics was observed. The measured locking band was small: a fraction of a percent of the center frequency. Optical injection locking of an S-band GaAs MESFET oscillator was reported in [34]. The locking range obtained was 5 MHz, for an estimated absorbed optical power of the order of 1 μW. When locking effects occur, a substantial reduction of the FM noise of the MESFET oscillator, associated with locking to the more stable modulation signal applied to the laser, was obtained. An approximate analysis of optical injection locking of GaAs MESFET oscillators is given in [37]. For a low injection level of the locking signal, the approximate expression for the locking range is

$$2\Delta\omega = \frac{\omega}{Q_t} \cdot \frac{g_m}{\omega C_{gs}} \cdot \frac{|I_L|}{(2 \cdot P_{\text{out}} \cdot G_L)^{1/2}} \tag{3}$$

where $2\Delta\omega$ is the locking range, ω the center frequency, Q_t the unloaded Q factor of the gate circuit, g_m the transconductance of the device, C_{gs} the gate-to-source capacitance, I_L the locking photocurrent, P_{out} the free-running output power, and G_L the conductance of the load presented to the FET terminals. For the typical values used in the experiment at 2.8 GHz ($g_m \sim 40$ mS, $C_{gs} \sim 0.8$ pF, $P_{\text{out}} \sim 2$ mW, $I_L \sim 10$ μA and $Q_t \sim 70$), equation (3) gives a locking range around 1 MHz, in quite fair agreement with the few MHz locking range found experimentally [7], [34]. Recently, analysis and experiments of direct optical injection locking of a common-source GaAs MESFET oscillator [38] and experiments together with a SPICE simulation model for prediction of optical injection locking range [39] were reported. The measured results show locking ranges of the order of 4.5 MHz at frequencies of 2.4 and 2 GHz, respectively. Also a simple technique was proposed and demonstrated for controlling the phase of an optically injection-locked 7.2 GHz FET oscillator [40]. An injection locking bandwidth up to 2.6 MHz and a phase tuning range up to 187° have been observed.

The locking ranges so far achieved could be substantially improved by more efficient coupling of the modulated laser light to the active area of the device and by more efficient coupling of the microwave locking signal to the laser chip. Parts (a) and (b) of Fig. 4 illustrate two possible alternatives to improve the optical absorption in the active area of the MESFET [7]. The structure of Fig. 4(a) is also known as an INGFET (inverted gate FET) and has been studied recently [41]. The use of a lower Q factor oscillator circuit could also be of moderate benefit in increasing the locking range. Further, control of the intensity of the optical carrier could be used to pretune the oscillator to a frequency close to that of the locking signal, thereby providing large operational bandwidths. Also, the possibility of locking with optical modulation frequencies close to subharmonics of the oscillator frequency is suggested by the inherent nonlinearity of the device active channel. Recently, experimental results for a system combining optical injection locking and closed-loop optical

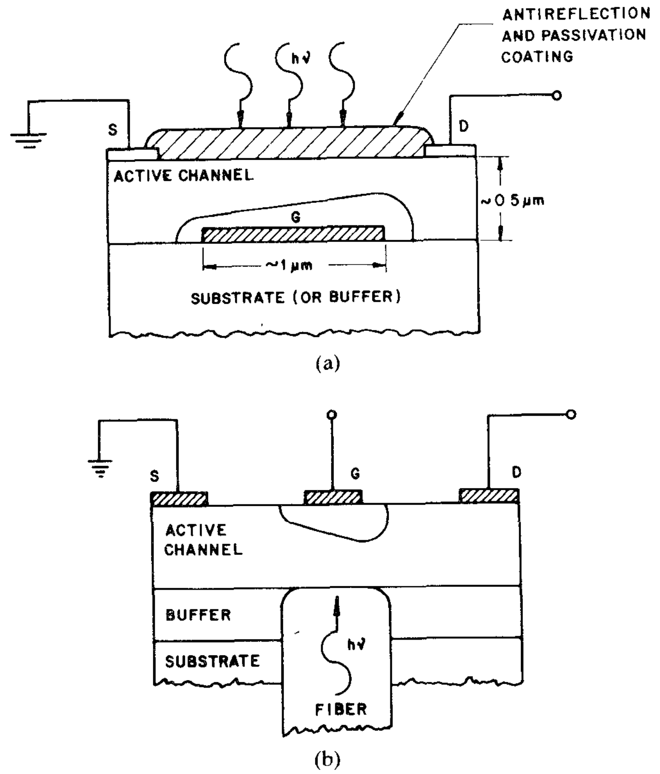

Fig. 4. Two possible alternatives to improve the optical absorption in the active area of the MESFET [7]: (a) buried gate MESFET and (b) illumination through the substrate.

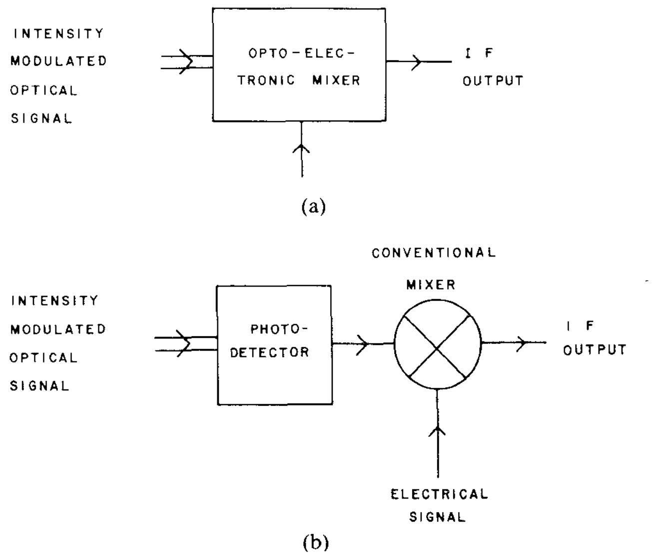

Fig. 5. (a) Optically pumped mixer and (b) equivalent using conventional components.

frequency tuning to achieve accurate phase and frequency control of a GaAs MESFET oscillator operating at 1.3 GHz were reported [42]. Compared with a system using only injection locking, the combination of these two techniques reduces the phase error across the locking range and also improves the noise suppression within the injection locking range. This technique might be adequate for the phase synchronization of the oscillators in phased array antennas, where the phase reference is distributed by an optical-fiber network.

Finally, HEMT's appear very promising devices for direct optical injection locking. Calculations have shown an increase in the gate and drain capacitance and a decrease in the gate charging and the channel resistances with illumination [10]. These capacitance variations with optical illumination can be successfully exploited in the design of injection locked oscillators for integration with other MMIC or OEIC components.

IV. Optically Pumped Mixers

Fig. 5(a) shows the principle of the optically pumped mixer. The signal input to the device is electrical but the local oscillator signal is supplied by an intensity modulated optical source. It is also possible to have devices in which the local oscillator input is electrical and the input signal is an intensity modulated optical signal, but these will not be treated in detail here. The device is functionally equivalent to a photodetector coupled to a conventional mixer as in Fig. 5(b). Integrating photodetection and mixing functions in a single device offers the attraction that electrical coupling at the local oscillator frequency between a separate detector and mixer, with consequent matching and parasitic component problems, is not required. There is also the attraction of simplicity.

A. Photoconductive Mixers

Photoconductive mixing has been achieved at frequencies up to 4.5 GHz in GaAs [43] and 0.1 GHz in InP based materials [44] with higher frequency operation predicted. The main difficulty is the optical power requirements for optically pumped operation, of the order of 10 mW for each mixer, which would make systems where considerable optical power division is required, such as phased-array radar, impractical.

B. Diode Mixers

These can be designed using either forward or reverse bias processes to provide the nonlinearity required for mixing. Gomes and Seeds [45] have carried out a detailed study of mixers using reverse bias tunneling nonlinearity. Fig. 6 shows the measured conversion loss for a Schottky contacted GaAs tunneling device using a directly modulated GaAs/AlGaAs laser, emitting a 780 nm wavelength, as the local oscillator source. For comparison, loss predictions from two computer modeling studies are also shown [45]. The minimum conversion loss was limited by the low responsivity of the mixer, resulting from the thin (~ 10 nm) tunneling region. Modeling studies [45] show that an optical power of 15 mW would be required at 780 nm wavelength to achieve 10 dB conversion loss. The development of visible-wavelength semiconductor lasers will considerably relax this requirement. However, the high capacitance, resulting from the tunneling region thickness combined with the requirement for sufficient device area for efficient optical coupling, suggests that the device is unlikely to prove useful at frequencies above a few GHz.

Gomes and Seeds [46] have proposed an alternative structure which uses forward bias nonlinearity in a Mott barrier junction. This is predicted to have conversion losses

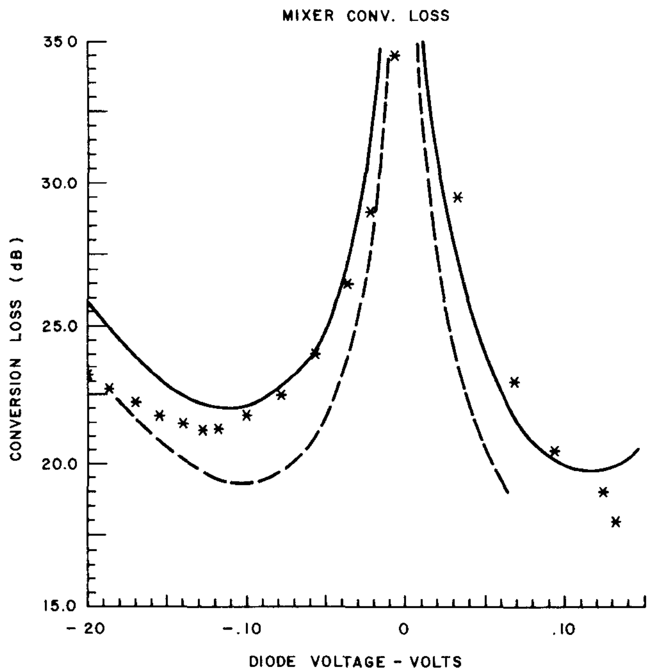

Fig. 6. Conversion loss of tunneling optically pumped mixer for input frequency of 100 MHz [45]: * experimental measurements; —— time-domain model; ---- frequency-domain model.

of 7 dB at 2.2 GHz and 11 dB at 10 GHz with an optical local oscillator power requirement of about 1 mW, values approaching those obtainable with conventional electrically pumped mixers.

C. Three-Terminal Mixers

The use of MESFET's as optically pumped mixers is of special interest because they are an essential active device in most MMIC designs; thus processing requirements are compatible.

Chu *et al.* [47] report pioneering experiments in which heterodyne optical sources were used to pump MESFET's with microwave and millimeter-wave signals. Fetterman and Ni [48] have used heterodyne optical sources to generate signals at frequencies up to 32 GHz in monolithic MESFET amplifiers and also describe optical mixing experiments in MESFET's [49].

Simons and Bhasin [9] reported preliminary experiments with an AlGaAs/GaAs HEMT optical mixer. A 6 GHz modulated laser beam illuminated the gate region of the device, a 9 GHz electrical signal was electrically coupled to the gate terminal, and the resulting IF signal at 3 GHz was taken from the drain terminal.

There is scope for much detailed work to characterize the optical mixing performance of MESFET's as well as to explore that of HEMT structures.

V. Discussion

It will be clear from this paper that considerable exploratory work has been done to produce optically controlled microwave devices for a variety of functions.

Most of the work has been carried out using standard or near-standard microwave device structures. This has led to inefficient coupling of the optical signal to the device and consequent limitations in performance. Modeling studies show that if the coupling could be improved, performance adequate for many systems applications would result. There is thus a challenge to device designers and fabricators to produce new device structures having good microwave performance and efficient optical access. The availability of advanced heterostructure and epitaxial growth techniques should make this goal a realizable one.

Of the devices discussed, MESFET's and HEMT's are of particular importance because they are the principal active devices for use in MMIC's. Novel optical control mechanisms for HEMT's, such as negative photoconductivity [50], make them of particular research interest.

Since much of the work carried out has been exploratory, there is a need for detailed studies to relate measured optical control performance to system requirements and to set target specifications for optically controlled devices. At the same time comparative models to relate optically controlled device performance to that of indirect control, using photodetectors to transfer the optical signal to the active device, would be helpful in establishing development goals.

With the advantages of optical systems for wide-band signal transmission already being recognized by systems designers, it seems clear that the second development phase, in which optical signals will act directly on microwave devices, will produce novel microwave systems of enhanced capabilities.

Acknowledgment

The authors are grateful to our many colleagues in this research area for sharing their views with us. Also, the first author would like to acknowledge the hospitality of the Catholic University of Rio de Janeiro, where much of this paper was written.

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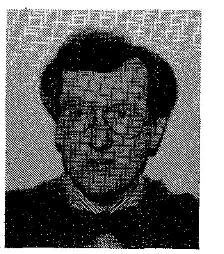

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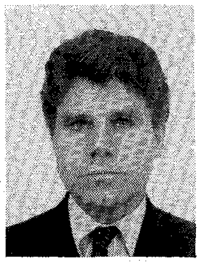

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