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NEW III-V TRANSDUCERS FOR OPTICAL MICROWAVE AND MILLIMETER WAVE CONVERSION

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ABSTRACT : Fiber optic radio communications will require devices able to convert an optical carrier into a millimeter wave carrier. After a brief recall of possible systems to be used, showing that in most cases, the transducer must associate the following functions : high speed photodetection, millimeter wave amplification, and mixing, we will discuss the properties of PIN-waveguide photodetectors, GaAs microwave monolithic integrated circuits with dual gate FETs, InP edge-coupled Heterojunction Bipolar Phototransistors to fulfill these requirements.

INTRODUCTION

Fiber radio links are a possible alternative to other techniques such as Fiber to the Home or electrical cables for local distribution of information. Frequency range of interest could be the millimeter wave domain. This imposes to study and develop systems using both fiber networks and radio transmission in the millimeter wave frequency range. In these systems, the data are carried by the optical signal in the fiber network up to an optical millimeter wave transducer which converts the optical carrier into a millimeter wave carrier before the antenna level. In this paper, we will first recall possible systems to be used and give examples of systems under study in Europe ; we will show that optical microwave transducers must fulfill one or several of these functions : mixing, high speed photodetection, millimeter wave amplification, optical control of microwave oscillator. We will then illustrate our purpose with three examples of devices : monolithic association of MSM with dual gate FET on GaAs substrate, InP PIN waveguide photodetector, InP edge coupled Heterojunction Bipolar Phototransistors.

I. MILLIMETER WAVE OPTICAL LINKS

I.1. Direct modulation of lasers

The link is then just constituted of a directly modulated laser, an optical fiber and a high speed photodetector. It is the simplest solution. Nevertheless, for wavelengths of interest in optical communications systems (1.3µm - 1.55µm), cut-off frequency of InP lasers are still too small to reach 40 or 60 GHz. Best results (30 GHz) reported with a bi-section DFB 1.55 µm InP laser [1], are based on a new modulation technique proposed several years ago [2] which is the modulation of absorption in a small part of the cavity. Consequently, up to now, systems based on this technique cannot be implemented for millimeter wave optical links.

I.2. Use of laser non linearities

Because of the limited cut-off frequency of lasers, one possible solution, to overcome this limitation, is the use of laser non-linearities. The technique is based on direct modulation of lasers, but a large microwave signal is applied on a conventional high speed laser. Because of intrinsic laser non-linearities, we can generate harmonics at the output of the link and reach then the useful millimeter wave frequency signal, with a laser whose cut-off frequency is lower. Such a system working at 38 GHz [3] was recently demonstrated; this system uses commercially available active devices and the frequency of the microwave signal applied on the laser is 7.6 GHz; the 38 GHz signal at the output of the high speed photodetector is obtained thanks to the fifth harmonic.

I.3. External modulation

Amplitude optical modulator, with cut-off frequency around 50 and 60 GHz was demonstrated [4,5], but these devices are still laboratory prototypes, and are really not commercially available, except for devices with cut-off frequency around 40 GHz [6]. Moreover the system is generally more complicated to implement and suffer from insertion losses of the modulator, and the required modulation power which is generally high.

I.4. Heterodyning technique

It is also a promising technique based on the beating of two optical signals which optical frequency difference is equal to the frequency of the millimeter wave signal to be generated. The difficulty is to keep the coherence between the two optical signal after propagation in the optical fiber. For example, in the european projects MODAL and FRANS, thanks to an external amplitude modulator two side bands appear in the optical spectrum when a microwave signal is applied on it ; these two lines can play the role of the two optical sources if the frequency of the microwave signal is half of the millimeter wave frequency and if a filtering is made to cancel the central optical line. This technique was applied with success to deliver signal from one base station to several antenna units [7], demonstrating that it overcomes chromatic dispersion effects. Nevertheless, this technique is also heavy to implement.

I.5. Optical control of microwave oscillator

In all the previous systems, a very high speed photodetector is needed. Another technique, which does not absolutely need a high speed photodetector, is the optical control of a microwave oscillator. It consists of modifying the characteristics (amplitude, phase or frequency) of the millimeter wave signal generated by the oscillator, thanks to the optical signal impinging on the oscillator. Consequently a part (active or passive) of the oscillator, must be highly sensitive to illumination. The speed of this element can be those of the data to transmit which is far below the radio carrier millimeter frequency.

A lot of works were devoted to this topic, trying to play with an active or passive device [8-18], and to study the sensitivity to illumination.

I.6. Discussion on systems aspects

Several systems were proposed, generally based on principles described before (see for example [3,7,19-22]. Except for the last one, all these techniques use a high speed photodetector, which cut-off frequency is higher than the frequency of the millimeter wave signal to generate. Moreover, the intensity at the output of the photodetector is generally very low and amplification is needed. Millimeter wave amplifiers must then be associated to the photodetector to get enough signal for supplying antenna. At last, all these considerations were made for one way link corresponding to radio emission. In fact, for telecommunications purpose, a return way is needed (radio receiver and transmission down to the base station). For this return link, the radio transmission is also in the millimeter wave frequency range, and to make easier the optical fiber transmission return link, a good solution seems to convert the frequency of the received radio signal down to a frequency lower than the cut-off frequency of commercially available lasers. As a consequence, mixing techniques are needed in the transducer.

To illustrate our purpose, we will now consider three types of devices : monolithic association of MSM with dual gate FET, PIN waveguide photodetector and edge coupled heterojunction bipolar phototransistor and examine their ability to perform one or several functions needed for a transducer.

II. ASSOCIATION MSM-DUAL GATE FET

This could be classified in the category of optical control of microwave oscillator. For III-V circuits fabricated in foundries, one possible way to make a device sensitive to illumination is to associate a photodetector and a mixer (or amplitude modulator) to the microwave oscillator. The electrical signal delivered by the photodetector is then mixed to the signal of the oscillator ; we get then, at the output of the mixer, the millimeter wave signal of the oscillator modulated in amplitude by the data signal which modulates the amplitude of the optical signal. The cut-off frequency of the photodetector is related to the maximum frequency of the data signal. Different methods of optoelectronic mixing were proposed [23-28]. Here we show a mixing function obtained with a dual gate field effect transistor. Each signal (issued from the photodetector and the oscillator) is applied on each gate of the transistor. At the output (the drain), we get the product of both signals. The photodetector can be associated to the mixer and the oscillator using hybrid or monolithic techniques. To illustrate this purpose, a device associating a GaAs Metal Semiconductor Metal (MSM) photodetector with a GaAs dual gate MESFET was fabricated [29]. For compactness purpose, the MSM was monolithically integrated to the transistor. Since the MSM is made with Schottky contact deposition on the buffer layer of the GaAs MESFET, the technology is compatible with the one of the transistor and the MSM can be made during the same step than the transistor gate. Of course, this monolithic integration limits the photodetection to wavelengths shorter than 0.85µm and cannot be applied to long wavelength (1.3-1.55µm) applications. Nevertheless, transmission could be made, for example for indoor applications, with GaAs VCSEL's, or edge emitting GaAs lasers. Moreover, the important aspect is to show the mixing (or modulation) properties between a data signal which modulates an optical carrier (here at 0.85µm) and a local oscillator signal in the microwave or millimeter wave domain. This is illustrated in figure 1 where we show the conversion factor which corresponds to the ratio between the power of the mixed signal at the output and the power of the signal at the output of the photodetector. This experiment was made versus frequency of local oscillator for a data signal at 100 MHz. The frequency domain of the local oscillator is here limited to 1-10 GHz which corresponds to the working bandwidth of the transistor, the technology being not optimized for millimeter wave applications. A good conversion factor is obtained, due to transistor gain effect, thus demonstrating the potentialities of this method for mixing function.

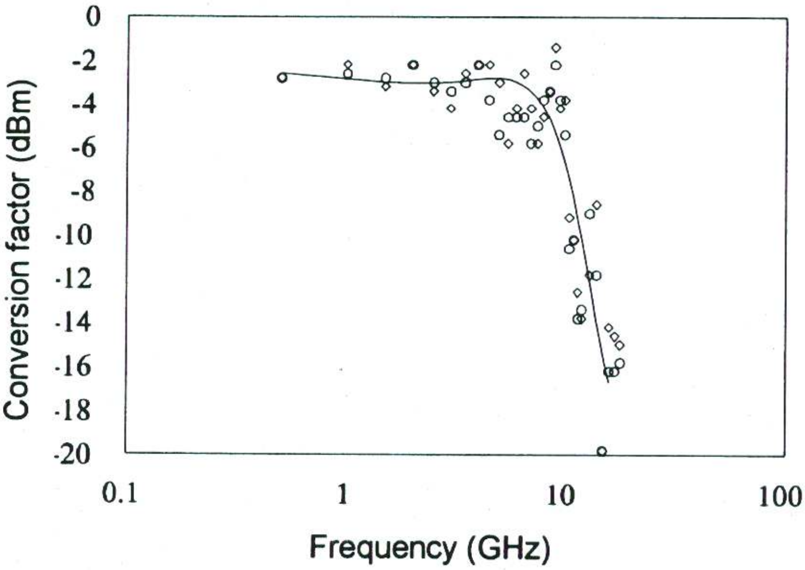

Figure 1: Conversion factor for a MSM photodetector monolithically associated with a dual gate GaAs MESFET versus local oscillator frequency. Data signal frequency is 100 MHz.

III. PIN-WAVEGUIDE PHOTODETECTOR

It is now well-known that the InP PIN-waveguide photodetector is a good candidate for high speed (1.55µm or 1.3µm) photodetection in the millimeter wave region with high quantum efficiency [30]. High speed top or back side illuminated photodetectors suffer from low responsivity when increasing cut-off frequency for millimeter wave applications. This is due to the reduction of the thickness of the active absorbing layer needed to get a short transit time. Edge-illuminated PIN waveguide photodiode overcomes the trade-off between responsivity and cut-off frequency, since the device can be long enough to reach a high responsivity together with a thin absorbing layer to provide a high cut-off frequency ; also, because the dimensions are small, the capacitance related to the junction surface does not induce a large penalty from the frequency point of view. To have a good coupling efficiency between the optical fiber and the photodiode, the latter is designed to be multimode. At last, the microwave access is of prime importance, and generally, coplanar line is adopted to be compatible with millimeter wave MMIC's. Several demonstrations [31,32] were made with devices whose structure is similar to those of figure 2, showwing a high responsivity as well as a high cut-off frequency. This demonstrates the high speed photodetection capability of these devices.

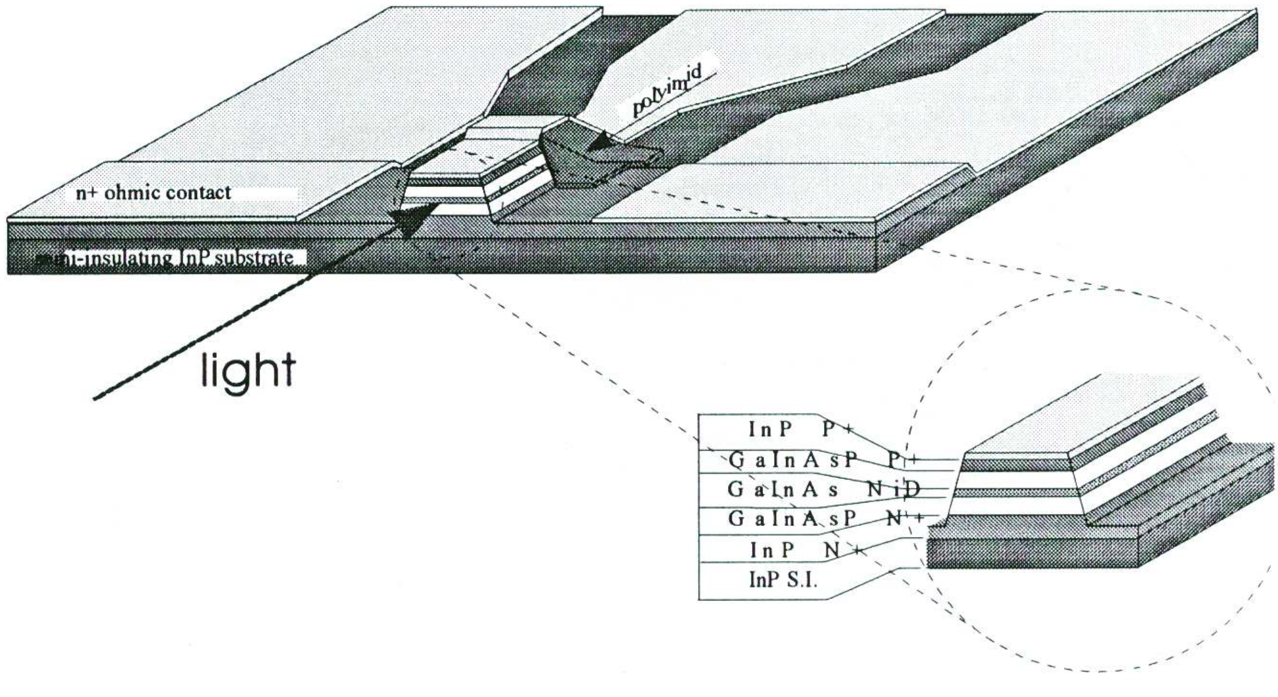

Figure 2: Typical PIN-waveguide photodiode structure with coplanar microwave access.

We can also mention that the transfer of the millimeter wave signal in a small bandwidth can be improved around the working frequency by using a reactive passive matching network associated to the PIN photodiode. The principle is to transform the 50Ω impedance into a higher impedance in the bandwidth of interest. This was already demonstrated in the microwave domain using hybrid or monolithic association [33,34] and such a technique is now under investigation for the millimeter wave frequency range (28-30 GHz). First results are encouraging [35]. It can be noted that the behavior of these devices was also modeled under high optical illumination [36]; a maximum millimeter wave power available at the output around 0 dBm was predicted.

IV. EDGE COUPLED HETEROJUNCTION BIPOLAR PHOTOTRANSISTORS

It is necessary to amplify the millimeter wave signal at the output of the high speed photodetector. This is generally made using millimeter wave MMIC's fabricated in GaAs foundry. Because the materials of 1.3-1.55μm wavelength photodetector are InP based, hybrid association is required. Instead of monolithic association with transistors, internal gain photodetectors can be used. Avalanche photodetectors are attractive, but suffer from excess noise factor and important bias voltage.

A few years ago, D. Wake [37] proposed the use of edge-coupled InP heterojunction bipolar phototransistors (HPT's). He demonstrated the millimeter wave photodetection capability of a two terminal edge coupled HPT with a unity gain frequency (corresponding to a PIN waveguide photodiode level) around 30 GHz. A typical structure of a two terminal edge coupled HPT (2T HPT) is given in figure 3. As for PIN waveguide photodetector, the edge illumination permits to achieve a high quantum efficiency with typical HBT base and collector thickness.

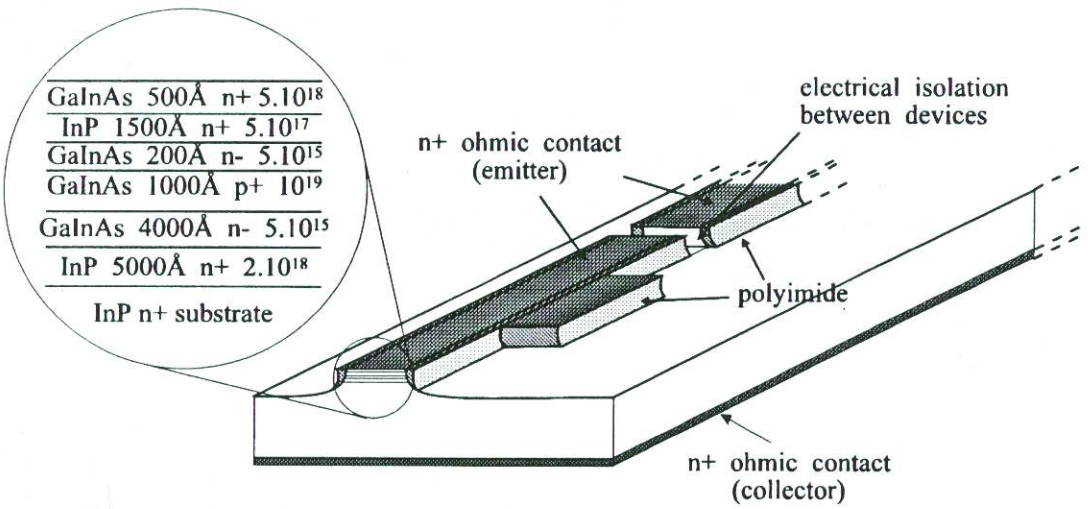

Figure 3: Schematic view of a edge-coupled 2T-HPT.

Recently was demonstrated electro-optical mixing with 2T-HPT's [38,39]. This function is a consequence of gain non-linearities and as an example, in [38] experiments were performed with an optical signal modulated at 2 GHz (RF signal) and another one modulated at 2 KHz (square wave signal); the two optical signals were applied simultaneously to the 2T HPT, and the resulting signal at the output is the amplitude modulation of the 2 GHz microwave carrier by the 2KHz data signal to transmit. Because of the attractive properties of the edge coupled heterojunction bipolar phototransistor which combines high speed photodetection, amplification and mixing, a three terminals edge coupled heterojunction bipolar phototransistor (3T-HPT) was fabricated with a base connection [40]. The epitaxial layer is similar to the previous one, except for the thickness of the emitter, which is thicker (1.5µm instead of 1500 Å) in order to allow the self-aligned base deposition. Experiments carried out with this device confirmed the excellent properties of high speed photodetection and amplification in the millimeter wave domain with a unity gain frequency around 40 GHz. Mixing experiments were also performed with one signal directly applied onto the base and the other one modulating the amplitude of an optical signal absorbed by the 3T-HPT. Here again, non-linearities occur, and at the output a microwave carrier which amplitude is modulated by the optical transmitted data is obtained [40].

The 3T-HPT is also a bipolar transistor which can easily be controlled by light. Experiments given in [40] show that an optical power of 1 mW impinging on the device is equivalent to a base current of

150-200 mA when coupling is made with a cleaved fiber, and three times more with a lens ended fiber. It means that a sufficient power can change the bias point of the device, and then its characteristics. For example, it could switch between one state without gain to a state with gain, the switching being made with light power, playing the role of a supplementary base current. This is also an interesting property and works on this topic are in progress, with demonstration of optical control of a microwave oscillator [41].

At last, modeling of this device is absolutely needed for optimization. A complete electrical and optical modeling was recently developped [42], showing that the responsivity can be improved from 40% to 60% (with a lens-ended fiber), by adding a supplementary GaInAsP quaternary layer as part of the subcollector between GaInAs collector and InP subcollector. This modeling also predicted a unity gain frequency higher than 60 GHz.

CONCLUSION

Fiber radio communications in millimeter wave domain require transducers which associate several functions :

- high speed photodetection
- millimeter wave amplification
- mixing properties
- optical control of microwave oscillator

The present followed way, is the hybrid association of InP PIN waveguide photodetector and GaAs millimeter wave MMIC's (for amplification and mixing). Nevertheless, based on recent results presented here, other ways can be suggested and are listed below :

- Hybrid association of commercially available InGaAs PIN photodiode with GaAs MMIC's made in III-V foundry, integrating functions such as : millimeter wave oscillator, mixer (for example, made with dual gate FET's) to modulate the millimeter wave signal, mixer to down-convert the frequency of the return link signal.

- Hybrid association of edge coupled HPT's with GaAs MMIC's. In this case, the HPT takes the place of the PIN-waveguide photodiode and we just take benefit from the internal gain of the phototransistor to improve the signal to noise ratio.

- Millimeter wave oscillator fabricated with 3T-HPT's in order to optically control the characteristics of an oscillator, and then to modulate the millimeter wave signal (AM, FM or PM).

- Monolithic association of edge coupled HPT's with millimeter wave circuits made with HBT's, using the technological and epitaxial compatibility of HBT's and HPT's. These circuits could combine photodetection, amplification and mixing functions. But some efforts are needed to make this technology mature for foundry.

To conclude, we can say that the choice between all these possibilities will depend upon criteria such as : performance, cost, reliability, size, ... and existence of a mature technology to meet the requirements of a future market.

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