Ultrafast InGaAs photoswitch for RF signal processing

R. Horvath[1,2], J- F. Roux[1], J- L. Coutaz[1],
J. Poëtte[2], B. Cabon[2]

[1]Univ. Savoie Mont-Blanc, CNRS, IMEP-LAHC
Le Bourget du Lac, France
[2]Univ. Grenoble Alpes, Grenoble-INP,
CNRS, IMEP-LAHC
Grenoble, France

C. Graham[3]
[3]University College London, Department of Electronic and
Electrical Engineering
London, United Kingdom.

Abstract — **Optical processing of radiofrequency signals is demonstrated in this communication using photoswitches made from nitrogen ion implanted InGaAs. The sampling device shows an ultrafast picosecond response time while activated by ultrashort optical pulses or modulated optical beam centered at the wavelength of 1.55 µm. The optoelectronic device is embedded in a microwave coplanar waveguide which has a high electrical bandwidth allowing to process signals in the 1-67 GHz band. We investigate the potentiality of this component to be used either in photonic assisted sampling for future analog-to-digital converters or in photonic assisted heterodyne detection of RF modulated carriers.**

Index Terms — **Photoconductive sampling, ion implanted InGaAs, ultrafast electronics, metal-semiconductor-metal devices, radio over fiber, photonic assisted data processing, heterodyne photomixer.**

I. INTRODUCTION

Microwave photonics is a technology area which includes generation, processing, analog-to-digital conversion (ADC) of microwave signals using optoelectronic technological bricks such as laser, modulators, detectors and fibers. It is at the heart of future fiber and wireless telecommunication networks. Indeed, recent development of high performance optoelectronic components has permitted to reach the so-called THz communication band and wireless communications above 100 GHz have been demonstrated, allowing higher data rate transmission [1]. In such a technological framework, the use of complex well-proven modulation schemes already used at lower frequency is challenging to reach multi-GBits/s data rate. However, such modulation requires additional signal processing at the receiver location such as heterodyne detection together with numerical data post-processing which is usually handled by specific digital signal post-processing [2]. In order to gain performances and offer cost-effective or robust solutions it might be interesting to propose photonic assisted processing of the received radiofrequency (RF) signal modulated by the complex data stream. For instance, the use of ultralow jitter laser sources could increase the performances of the receiver by one order of magnitude as compared to full-electronics approach for ADC of GHz RF signals [3]. In such high

bandwidth applications, one key function is the mixing of RF and optical signals. It requires that the mixing process offers very high bandwidth together with linear responses to both the optical and electrical signals. For that it has been shown that simple metal-semiconductor-metal photoswitches (PSW) made from low-temperature-grown GaAs reach these requirements and could be used as mixer. Hence, this component has been used as ultrafast optoelectronic sampler for ADC [4, 5] and mixer showing applications in the RF band as well as in the THz one [6, 7]. Its principle rely on the increase of the electrical conductance of the semiconductor through absorption of the optical beam, making this device an optically controlled resistance. As compared to phototransistors that can also be used for such mixing, PSW do not require any DC bias to operate and consequently may strongly reduce the DC power consumption of the mixer. Unfortunately, this kind of GaAs based component is not fully compatible with the 1.55 µm telecommunication wavelength as GaAs is mostly transparent at this photon energy. In order to solve this problem, one may use InGaAs absorbing layers. Indeed up- and down- conversions of an input RF signal with frequency spreading up to 20 GHz with an optical Local Oscillator (LO) consisting of a modulated 1.55 µm optical beam have been demonstrated [8]. However, due to the long carrier lifetime in the InGaAs, the LO frequency was limited to 300 MHz, making this component not suitable for high data rate optoelectronic processing. Nevertheless, it is possible to strongly reduce this carrier lifetime in such semiconductor by introducing a large number of carrier trapping centers thanks to ion implantation or irradiation [9].

In this work, we investigate the use of Nitrogen ion implanted InGaAs PSW that shows an ultrafast carrier response time of less than 2 ps. We demonstrate that it can be used for optoelectronic mixing and sampling of RF signal in the 1 - 67 GHz band using lasers operating at 1.55 µm. For that we used either femtosecond fiber laser or self-modulating mode-locked laser diode at 60 GHz. These preliminary results open the way to more advanced studies in RF wireless communication systems in which high bit rate data streams will be sampled and/or demodulated by optoelectronic means using such a simple, low-cost and robust component.

II. DEVICE DESCRIPTION

The device that we are using in this paper is similar to the PSW preliminary studied in [10] where it has been shown that it possess picosecond response time and good dark resistance. In this previous work the InGaAs PSW has been used to demonstrate simple switching experiment at frequency up to 15 GHz. The component consists of a coplanar waveguide (CPW) which central line (width 25 μm) is interrupted by a 25 μm gap with interdigitated fingers as shown in the inset of Fig. 2. The fingers may be of different numbers (3 to 5) and their separation is consequently varying from 3 to 5 μm. The coplanar waveguide is about 750 μm long and is made from gold electrodes deposited on a Fe:InP substrate. At the location of the 25 x 25 μm² gap, a 300 nm thick mesa of InGaAs was deposited onto the substrate. The device is then irradiated with Nitrogen atoms that create a large number of defects in the InGaAs layer and then penetrate deeply in the Fe:InP substrate. Considering the implantation parameters the concentration of EL2 type defects is estimated to be around $5 \times 10^{17} cm^{-3}$ ensuring a picosecond response time. In the following sections all the measurements were done "on wafer" using RF electrical coplanar probes.

III. DEVICE CHARACTERIZATION

As mentioned above, the electrical characteristics of the device (I-V curve and dark resistance) have already been measured in [10] and we have checked that most of our samples have kept similar characteristics. We then investigate in more details the high bandwidth properties of the PSW in terms of electrical and optoelectronical bandwidth. Before that we want to remind the basic operation of such an ultrafast PSW when illuminated by an optical beam. In the dark state, the lumped electrical equivalent model of the PSW is a capacitance C in parallel with a dark resistance Rdark (see the inset of Fig. 3). When illuminated by an optical beam with photon energy above the bandgap of the InGaAs layer, the conductance increase due to the photo-generation of free carriers in the absorbing layer. In a first approximation, the conductance varies linearly with the absorbed optical power. Its value depends on the geometry of the switch and also on the dynamics of the photogenerated carriers and their electrical properties such as mobility. In [5 and 6] we have studied the behavior of an ultrafast photoswitch illuminated either by femtosecond optical pulses or by amplitude modulated optical beams. In both cases, we have demonstrated that the temporal behavior of the device is mainly governed by the carrier lifetime of the electrons that can be roughly approximate by an exponential law e^{-t/τ_e} where τ_e is the carrier lifetime of the photogenerated electrons.

In order to investigate the dynamics of the optoelectronic response of the samples, we have performed optoelectronic autocorrelation [11]. The experimental setup is shown in Fig. 1, it consists of illuminating the PSW with two femtosecond pulses that are delayed by Δt one from each other thanks to an optical delay line, while the PSW is DC biased and loaded by a 50 Ω resistor. The delay, Δt, is continuously varied and we record the average voltage observed at the load resistor. Because the PSW acts as a voltage divider with the load

resistor the overall circuit shows a non-linear response to the optical pump excitation. Consequently, as compared to the case where the two exciting pulses are separated by a time much larger than the PSW response time ($\Delta t \gg \tau_e$), the recorded signal is decreasing as long as the time delay in between the two pulses is reduced: the autocorrelation signal is minimal at $\Delta t = 0$. Moreover, the temporal behavior of the optoelectronic autocorrelation trace gives a direct insight about the PSW temporal dynamics if the duration of the exciting optical pulses is much shorter than τ_e.
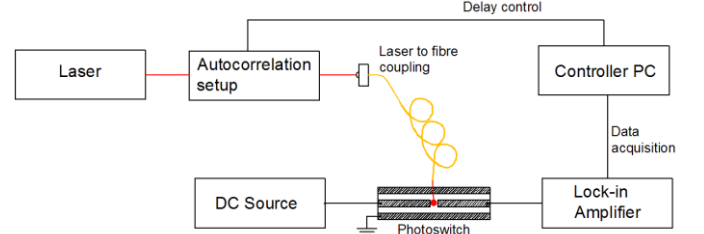

Fig. 1. Experimental setup to measure the optoelectronic response of the photoswitch. The fibre end was cut and aligned for precise illumination of the InGaAs mesa.
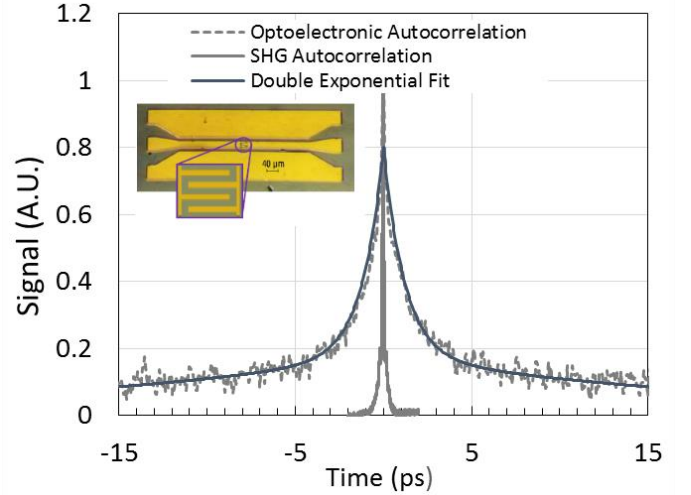

Fig. 2. Optoelectronic (dashed grey line) and optical (grey line) autocorrelation traces of a Nitrogen implanted InGaAs PSW (inset). A double exponential fitting curve with time constants of 1.2 and 20 ps is also shown (black line).

Here we perform the experiment with a fiber femtosecond laser operating at 1.55 μm (MENLO C-Fiber) with a repetition rate of 100 MHz. The two delayed optical pulse trains are propagating toward the switch through 3 meters of SMF 28 fiber which linear group velocity dispersion is compensated by a section of dispersion compensation fiber with -38 ps/nm/km dispersion factor. We checked that the duration of the optical pulses at the output of the fibers is limited to less than 100 fs by measuring the optical autocorrelation trace thanks to second harmonic generation in a BBO non-linear crystal. This optical autocorrelation trace is plotted in Fig. 2 (continuous grey line) it gives also the zero delay (Δt= 0) time of the experimental set-up. Finally, we record the optoelectronic autocorrelation signal for average optical power of 1.5 and 2.5

mW for each of the two delayed beams. A typical result is plotted in Fig. 2 (dashed grey line) it consists of a double side exponential function and shows a very sharp peak around zero delay which is a signature of residual optical interference between the two optical pulses. Ignoring this optical coherence peak, the optoelectronical autocorrelation trace is fitted with the formula: $A_1 e^{(-t/\tau 1)} + A_2 e^{(-t/\tau 2)}$. We found the best fit for A1=0.6, A2=0.2 and τ_1= 1.2 ps while τ_2= 20 ps (black line). These ultrafast time constants confirm the picosecond response time of these nitrogen implanted InGaAs PSW [10]. Here we show that the 4.4 ps response time that was observed in [10] with an ultrafast oscilloscope was certainly limited by the bandwidth of the electronic sampling heads. From the 1.2 ps response time of the PSW, we expect a cutoff frequency of the device larger than 100 GHz. The longer 20 ps time constant that we observe may either be attributed to a contribution of holes or to an electron de-trapping time; its lower amplitude reduces its impact on the overall optoelectronic bandwidth of the PSW.

In a second experiment, we have checked the electrical bandwidth of the device by measuring its S parameters in the dark state using a 0.04 – 65 GHz vector network analyzer. The experimental frequency evolution of the S_{12} parameter is plotted in Fig. 3 together with the theoretical curve obtained considering the basic lumped element equivalent model of the gap. We found an equivalent capacitance of 5.7 fF and a dark resistance of 5 kΩ. This low capacitance, also insure an ultrafast RC response time shorter than 300 fs for a 50 Ω load impedance.
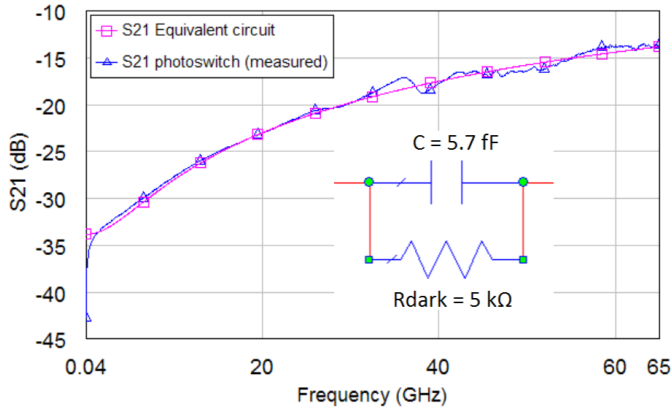

Fig. 3. S21 parameter of the PSW in the dark state. The inset shows the lumped elements equivalent circuit of the device.

IV. PHOTOCONDUCTIVE SAMPLING OF RF SIGNALS

After characterization of the fabricated structures we have used them to demonstrate their ability of sampling RF signals. Here we have chosen an asynchronous sampling experiment in which the RF signal is free running while the sampling frequency is fixed by the repetition rate of the femtosecond laser (F_{laser} = 100 MHz). The electrical input of the PSW is directly excited by the AC output of an Agilent RF Synthesizer E8257 D working in the 250 kHz - 67 GHz band with enhanced power mode (up to +15 dBm). In this experiment, the PSW is not DC biased but it is optically

activated by the train of fs pulses delivered by the femtosecond laser already described above. The RF output signal of the PSW is characterized with a spectrum analyzer (Anritsu MS2667C of 30 GHz bandwidth). Fig. 4 shows the experimental setup.
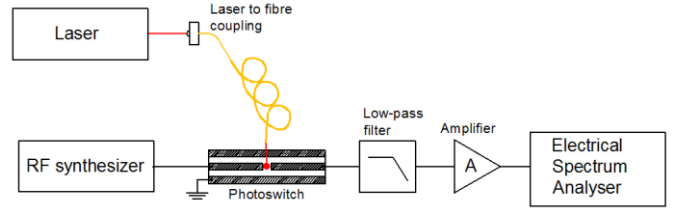

Fig. 4. Photoconductive sampling experiment setup.

As shown in [5] when excited by an RF signal of frequency F_{RF}, the illuminated PSW delivers a train of electrical pulses at the repetition rate F_{laser}, which amplitude depends on the amplitude and the frequency of the RF signal, the optical power and the conversion efficiency of the switch. In the frequency domain, the electrical output consists of a Dirac-comb centred on the RF angular frequency F_{RF} with peaks separated by the frequency F_{laser} of the laser pulses train:

$$S(f) = \sum_{n=-\infty}^{n=+\infty} S_n(f) \times \delta\left(f - f_{RF} - n f_{laser}\right) \qquad (1)$$

The factor $S_n(f)$ is the amplitude of the nth harmonics of the frequency comb. It depends on the conversion efficiency of the switch which is decreasing when the RF frequency is above the cutoff frequency of the device. For RF input signals in the range from 1 to 67 GHz, we measured the power of the nth harmonic using an 80 dB amplification stage with 1 GHz bandwidth (see Fig. 4). So, we choose the nth harmonic which falls in the vicinity of 15 MHz. For example, if the input RF signal frequency is 30.015 GHz, the output of the PSW is a Dirac Comb centered around 30.015 GHz with harmonics every 100 MHz. The 300th harmonic of the sampled signal is positioned at 15 MHz and is thus amplified by 80 dB.
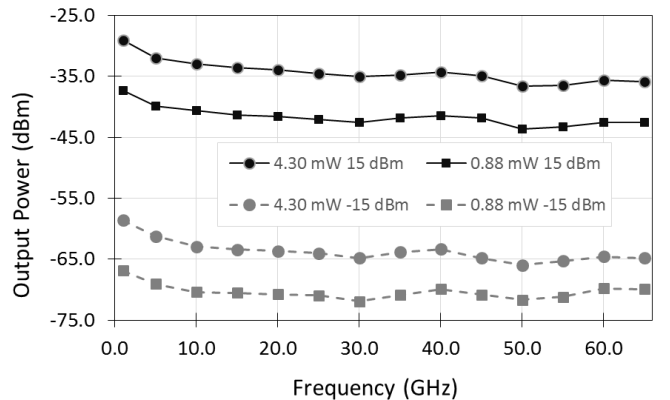

Fig. 5. Output power of the sampled signal for different experimental conditions: average optical power of 4.3 or 0.88 mW and RF power of - 15 dBm or + 15 dBm. The x axis represents the frequency of the RF input signal.

The results, compensated with the losses of the RF cables are plotted in Fig.5. The frequency dependent losses of the

cables were 0.6 dB for 1 GHz and 8.5 dB for 67 GHz. We observe that the amplitude of the sampled signal shows a small frequency roll-off. Actually, depending on the experimental conditions we observe only 4 to 6 dB of decrease in between the amplitude measured at 1 GHz and that measured at 67 GHz. This confirms the large bandwidth of the device. Moreover, by varying the input RF power from –15 dBm to 15 dBm we checked that the sampler output amplitude depends linearly on the input power. On the other hand we observe that at low frequencies the amplitude of the RF output increased by approximately 8 dB when the optical power is increased by 7 dB (from 0.88 to 4.3 mW). This means that in this regime, the RF output power varies almost linearly with the optical power whereas a quadratic law is expected for very low illuminating power (i.e. when the resistance of the PSW remains much larger than the 50 Ω load impedance) [5]. This experimental deviation from the theory might indicate that in our experiment, the circuit is working in a non-linear regime characterized by a very high peak conductance of the PSW under pulse illumination.

V. HETERODYNE DEMODULATION OF AMPLITUDE MODULATED RF SIGNALS

Another potential application of such ultrafast PSW is modulation or demodulation of RF signals with optical signals using the PSW as a hybrid (optical / electronic) mixer [6, 7]. Here we have investigated the potentiality of the InGaAs PSW to perform this operation in an experiment which is very similar to the previous one except for the laser. Here, the optical signal is a 1.55 μm CW beam modulated at a frequency F_{LO} and the RF input signal is at a frequency F_{RF}. These signals are mixed within the PSW, the flow of photocarriers that are generated by the absorption of the 1.55 μm optical beam being accelerated by the RF electrical field applied to the PSW. This mixing process results in an RF output signal oscillating at the intermediate frequency (IF) $F_{IF}=F_{RF}-F_{LO}$. Here again the RF frequency varies from 1 to 67 GHz while the RF power varies from -15 to + 15 dBm. As a modulated laser beam, we used an InAs/InP-based quantum dash mode locked laser diode self-oscillating at 58.625 GHz [12]. In order to compensate for the laser dispersion we use 70 m of SMF28 single mode fiber and a variable optical attenuator allows to vary the average optical power used to excite the PSW. The RF output of the PSW is detected thanks to a RF Spectrum Analyzer (RFSA) (Anritsu MS2668C 9 kHz – 40GHz). The experimental setup is similar as the one shown in Fig. 4, but without the filter and amplifier. For RF input frequency in the range of 19 - 67 GHz, the IF frequency falls within the allowed detection band of the RFSA. In Fig. 6 we have plotted the amplitude of this IF signal for an input RF power of 14 dBm. For an optical power of 5 mW, the RF power at the IF is about -65 dBm leading to an estimated losses P_{IF}/P_{RF} of 80 dB.

We note that these large losses are within the same order of magnitude than the ones presented by unbiased ultrafast photodiodes used as optoelectronic mixer [13] and might been strongly reduce by smart engineering of the photoconductive device [7]. Similarly to the ultrafast photodiodes from [13],

our PSW presents an ultra large bandwidth of more than 65 GHz as confirm by its constant response over the whole frequency range except in the vicinity of 58 GHz where a systematic experimental decrease, which is under investigation, is observed. Finally, we have experimentally confirm the linear response of the photomixer versus the RF input power and we have demonstrated that the losses of the mixer might be reduced by increasing the impinging optical power (inset of Fig. 6).
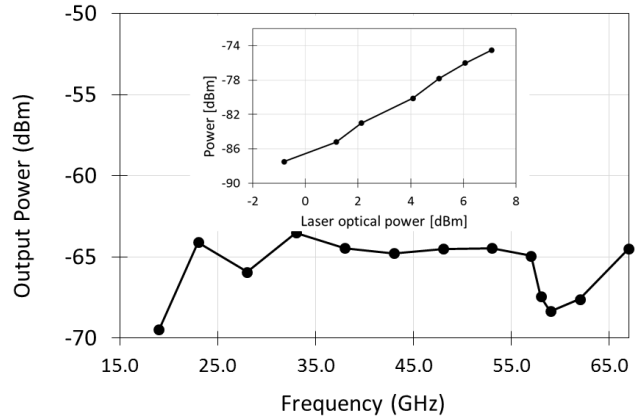

Fig. 6. Power of the IF signal for different input RF frequencies. The PSW is used as an heterodyne mixer in between a 14 dBm RF input signal and a 5 mW optical beam self-oscillating at 58.625 GHz. The inset shows the IF power dependence onto the optical power.

VI. CONCLUSION

In this work we have presented preliminary results of photoconductive sampling and mixing of RF signals using Nitrogen implanted InGaAs based CPW structures. The device is characterized by 5 kΩ dark resistance and low equivalent capacitance. Its optoelectronic response shows a very fast recovery time of 1.2 ps that allows us to demonstrate sampling of 67 GHz signals. Moreover we have performed heterodyne mixing in between an RF signal of frequency up to 67 GHz and an optical beam self-modulated at 58.625 GHz. These first demonstrations of principle are opening the way to demodulation and photonic assisted processing of high bit rate data streams carried either by the RF or by the optical signal.

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