Sub-THz wireless transmission based on Graphene on Silicon Nitride integrated photonics

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Abstract: We demonstrate the first wireless transmission based on graphene, using an integrated photonic device enabling up-conversion in the sub-THz range. Our approach opens the perspective to the realization of antenna arrays based on integrated photonics.

1. Introduction

The next 5G new radio (NR) and 6G wireless technologies are expected to afford the demand of high data-rate links, low-latency networks with maximized number of connected devices to enable new applications such as digital twins, AI computing, remote surgery etc [1]. To this end, novel hardware operating in the sub-THz range, allowing low phase noise, high signal integrity at $>$ 100 GHz carrier frequency, and tens of Gbit/s channel capacity will be necessay [2, 3]. The developement of this new hardware comprises superhetherodyne mixers performing up/down-convertion. Specifically, up-conversion of baseband information up to sub-THz carrier frequencies is highly desired [4, 5]. As the operating frequency increases, standard electronics shows its limits in terms of phase noise and signal integrity [6]. For these reasons, micorwave photonics techniques can be advantageously used to overcome these issues [7]. Indeed, ultra-wide bandwidth operation, wide tuneability and extremely stable radio-frequencies generation can be achieved using optical techniques. For example, frequency combs coupled to ultrafast unitravelling-carrier photodiodes have been used to demonstrate the generation of sub-THz frequencies up to 300 GHz exhibiting phase noise (PN) as low as 100 dBc/Hz at 10 KHz [8]. To obtain photonic-aided sub-THz upconversion, a single optical wavelength with frequency f_1 is modulated with a baseband data signal driving an optical modulator. A second optical tone with frequency $f_2 = f_1 + f_{LO}$ is combined with the modulated optical signal on a fast photodetector. The resulting beating is an electrical data signal at f_{LO} carrier frequency. Using this technique, several sub-THz multi-Gbit/s wireless links have been demonstrated [9].
The realization of antenna arrays in the sub-THz range, necessary in the next generation wireless access networks to improve antenna gain in a desired direction [3], requires high integration and small footprint matching the typical size of the sub-THz single antenna element ($\sim$ 1mm). The employment of two discrete and bulky active devices (modulator and photodetector) makes very difficult the use of photonic uptonverters for this application. Here we show a novel approach to implement photonic upconversion, by making use of a single integrated photonic device based on CVD-grown high mobility ($\sim 27000 cm^2V^{-1}s^{-1}$) wafer scale single layer graphene (SLG) crystals [10], with footprint $<$ 0.1 mm^2 performing the double functionality of sub-THz carrier frequency generation and frequency upconversion. We show frequency upconversion of multi-Gbit data signals up to 93GHz and demonstrate the first wireless trasmission based on graphene, exhibiting setup-limited perfromances.

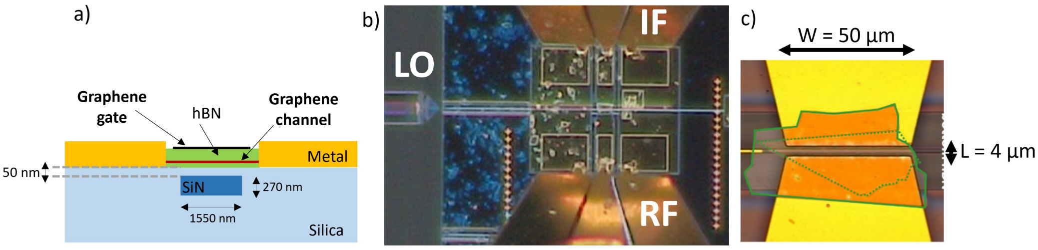

Fig. 1. Top view of the CPW and its cross-section with the quasi-TEM electromagnetic mode, at the level of the red cut line. The device has been fabricated using the dimensions indicated in the figure, which give a characteristic impedance $Z_0 \sim 50\Omega$

2. Results

Fig. 1a) shows a sheme of the fabricated device. A graphene layer encapsulated with h-BN is transferred on a SiN photonic waveguide with thin cladding ($\sim$ 50 nm). The waveguide is designed for TE single mode operation at 1.55 μm wavelength. The graphene layer is then embedded in the middle of the signal line of an electrical coplanar waveguide. Another graphene layer is placed ontop of the h-BN/Graphene/h-BN stack, acting as electrical gate. The photonic waveguide is coupled with an external laser source thrugh an inversed taper edge coupler allowing butt coupling with a monomode lensed fiber with $\sim 3\mu m$ mode field diameter. Fig. 1 b) is an optical image of the fabricated device and shows its operation as photonic upconverter. A dual wavelength laser source (LO) is coupled to the photonic waveguide. Light is absorbed in graphene through evanescent coupling with the photonic waveguide. This generates hot-electrons in grahene, which corresponds to a net change in its electrical resistivity [11]. Hot-electrons cooling in graphene is of the order of 2ps [12], allowing for very fast resisitiviy modulation. The time-dependent resisitivity change can be calculated as [11]:

$$\Delta R = \frac{1}{\Delta G} = \frac{L}{W}\frac{1}{\Delta\sigma} = \frac{L}{W}\frac{1}{\Delta\sigma + \Delta\sigma sin(2\pi f_{opt} t)} \tag{1}$$

Being ΔG the conductivity of the material, L the length of the graphene channel and W its width (see Fig. 1c)). f_{opt} is the frequency spacing between the two optical wavelengths. $\Delta\sigma$ is the amplitude of the conductivity change due to optical absorption. This last can be calculated from [11]:

$$\Delta\sigma = \sigma_{dark} - \sigma_{light} = \frac{D(\mu_c(T_{e,room}), T_{e,room})}{\pi(\Gamma(\mu_c(T_{e,room}), T_{e,room}))} - \frac{D(\mu_c(T_{e,hot}), T_{e,hot})}{\pi(\Gamma(\mu_c(T_{e,hot}), T_{e,hot}))} \tag{2}$$

In equation 2, σ_{dark} is the conductivity in dark condition, σ_{light} is the conductivity in illumination conditions, D is the Drude weight, Γ is the transport scattering time. These last two quantities depend on the graphene chemical potential μ_c and on the electrons temperature in dark (T_{room}) and illumination (T_{hot}) conditions. These quantities can be calculated by solving the heat equation for electrons considering hyperboic phonon cooling as principal mechanism of hot electron cooling in h-BN encapsulated graphene [13] and by accounting for charge carrier conservation [11]. By applying an electrical baseband signal to the coplanar waveguide $V_{in} = \widetilde{V_{in}} sin(2\pi f_{ele} t)$ (IF in Fig. 1 b)), the output voltage can be calculated. In the limit of graphene small conductivity change ($< 10\%$), the output voltage (RF in Fig. 1 b)) reads:

$$V_{out} \sim \frac{\widetilde{V_{in}} sin(2\pi f_{ele} t) R_L}{R_A + R_{dark}} + \frac{\widetilde{V_{in}} sin(2\pi f_{ele} t) R_L R_{dark}}{R_A + R_{dark}} \frac{W}{L}(\Delta\sigma + \Delta\sigma sin(2\pi f_{opt} t)) \tag{3}$$

Where R_A is the sum of generator, load and contact resistance, R_L is the load resistance, and R_{dark} is the graphene resistance in dark conditions. The second term in the last equation consists in the multiplication of the electrical signal with the optical local oscillator frequency, which corresponds to frequency upconversion. To demonstrate its operation, we used our integrated photonic optoelectronic mixer as upconverter inside the TX stage of a wireless link. The experimental setup is shown in Fig. 2. An optical local oscillator consisting in two phase-locked optical wavelengths separated in frequency by 91 GHz is coupled to the integrated photonic device. A baseband QPSK signal with datarate up to 4 Gbit/s and carrier frequency of 2 GHz is applied to the electrical coplanar waveguide. The resulting upconverted signal is then band-pass filtered, amplified and sent to a commercial receiver through a 2 meter wireless link. The retrieved baseband costellation is shown in 2. We measured an EVM of 27% at a datarate of 4 Gbit/s, corresponding to a BER of $1.3 \cdot 10^{-4}$ [14]. Fig. 2 also shows the EVM as a function of datarate. The

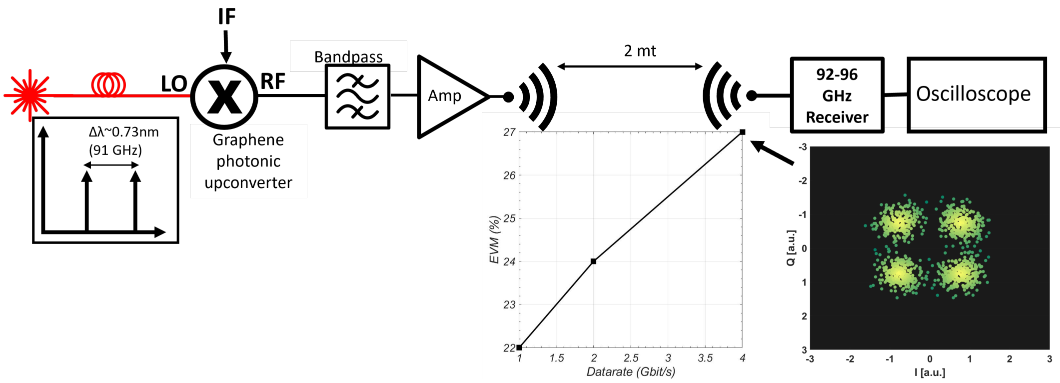

Fig. 2. Wireless link experimental setup and the resulting eye-diagram for a 4 Gbit/s QPSK signal. The plot shows the EVM of the received signal as a function of datarate.

SNR degradation is most likely due to the experimental setup itself, more specifically to the noise introduced by the active electronic components inside the wireless transmission chain, and to their limited electrical BW, this last being $\sim$2 GHz (with center frequency 93 GHz).

3. Conclusion

In conclusion, we demonstrated the first wireless link based on graphene. The result has been enabled by a compact integrated photonic upconverter allowing sub-THz carrier frequency operation and multi-Gbit/s datarate. The footprint of the device allows the realization of novel antenna arrays taking advantages of photonics, for the next generation 6G wireless communication systems.

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