Abstract – We present a concept for all optical Terahertz (THz) amplitude modulators based on a Fabry-Pérot (FP) filter design. By trapping the THz wave inside a cavity, an enhanced modulation can be achieved. The easy-to-handle and easy-to-fabricate design renders this concept very auspicious.

I. INTRODUCTION

Despite the fact that Terahertz Time Domain Spectroscopy (THz-TDS) has been used with great success over the past 20 years for various applications, there is still a lack of both passive and active system components. This shortcoming drives current research interests in the fields of filters, modulators and sensor devices for the THz regime [1-6]. But so far, most of the proposed concepts are either very complex in their realization, lack the required modulation speed or have insufficient modulation efficiencies. In this work, we present an easy way to fabricate, narrow-band-pass filters which show an outstanding modulation performance.

Fig. 1. Scheme of the modulator design. (a) illustrates the open band pass characteristics of the filter, while (b) depicts the inhibited transmission due to optical excitation of the cavity material.

Fig. 1 illustrates the key idea of the proposed modulator. A THz pulse is sent into a semiconductor disc based high-finesse etalon which consists of a highly transparent silicon wafer with two reflecting wire-grid surfaces. Chosen frequencies in narrow bands fulfill the standing wave condition of the cavity and can pass through the device in transmission direction while other frequencies are reflected [7]. Illumination of the wafer with a CW pump laser creates a free carrier plasma which interacts with the THz pulses. Those frequencies which are trapped inside the cavity exhibit a significant damping and thus, a high modulation contrast results at low optical power levels [8]. Similar techniques were demonstrated recently with more complex devices based one-dimensional photonic crystals [2,9]. The advantages of the proposed design lie in the easy manufacturability and the high modulation efficiency.

II. RESULTS

A high resistive silicon wafer with a thickness in the range of 450 µm and a refractive index of 3.4 [10] was utilized as a cavity. Via standard photolithography technics, two wire grids were applied to both surfaces in parallel to each other. The wires itself consist of a 10 nm titanium adhesion film and a 200 nm gold layer. The width of every wire is 30 µm as well as the spacing between them. Together, these wires build a polarization sensitive meta-surface. Such a surface acts as highly reflective mirror for the FP-cavity, if it is probed in parallel polarization.

Due to the high reflective boundaries of the cavity, a long train of FP-echoes results when the sample is characterized with THz-TDS [8]. In the frequency domain region, pronounced pass- and stop-bands result at multiples of the free-spectral range of the cavity. Fig. 2 shows the passive transmission characteristics of the fabricated modulator over a wide band from 0.2 to 1 THz (blue). One can observe narrow transmission bands ranging from 20% transmission (low frequencies) to nearly 90% transmission (high frequencies) with Q-factors between 100 and 300. Additionally, the transmission characteristics for several optical excitation powers are shown. In case of an illumination, one observes a remarkable inhibition of the pass-bands, depending on the optical power. Furthermore, there is almost no shift of the pass-bands by illumination with a laser. This indicates a minor change in refractive index due to the photo-excitation of the carriers.

Fig. 2. Spectral amplitude transmission of the measured wafer without optical excitation and for chosen values of the excitation power.

Fig. 3 shows the frequency characteristics of the individual transmitted FP-pulses by using a Short-time Fourier transform (STFT). On the left side (0 W) there is no optical excitation of
the cavity. Hence, one is able to observe the frequency behavior of the echo pulses in the bare filter.

On the right side of Fig. 3, the STFTs of two optical excitation powers, a weak one (0.52 W) and a high one (2.28 W) are shown. Particularly the low frequency components are significantly attenuated by the optical excitation. Two mechanisms forge these characteristics: i) The wire-grid surfaces have a higher reflectivity for longer wavelengths and thus, small frequency components have a longer average photon-lifetime inside the cavity. ii) The plasma frequency is in the range of about 1 THz and thus, a strong absorption results for lower frequencies.

As a consequence the modulation efficiencies for one specific excitation power vary between the different pass-bands. In the lower frequency region the conditions favor higher efficiencies (Fig. 4). But between 550 GHz and 1 THz and for an excitation power above 2.28 W, the modulation depth off all pass-bands is above 90%.

Since the modulation speed of the device is mainly contributed to the lifetime of the free carriers in the silicon substrate, the achievable modulation frequency should be in the range of 1 kHz. Faster realizations of this concept are possible by utilizing a cavity substrate with shorter carrier lifetimes, like a direct band-gap semiconductor as Gallium Arsenide.

### III. Summary

In conclusion we demonstrated an efficient THz amplitude modulator consisting of a semiconductor wafer with metasurfaces on both sides to achieve a cavity of high finesse. By illuminating the semiconductor, free carriers emerge and damp those photons in the cavity more efficiently, which have a longer lifetime. At an operation frequency of 942 GHz and 2.28 W of optical excitation, the demonstrated device exhibits a modulation depth of more than 90% and an insertion efficiency above 80%.

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### References


