A Travelling-Wave Uni-Travelling Photodiode for Continuous Wave Terahertz Generation

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Abstract: The combination of fast carrier transport with the advantages of employing a travelling wave design can expand the performance of photodiodes both in terms of responsivity and frequency response. Thus, the resulting ultra-fast photodiode integrated with an antenna can be used as the photomixing element in order to generate a continuous wave Terahertz signal.

1. Introduction.

The development of Terahertz frequencies systems, ranging from 100 GHz to 10 THz is expected to lead to a wide range of applications [1]-[2] including biology and medicine [3], imaging [4], communications [5] and security [6]. So far, the technology that is available in these frequencies is rather limited due to the difficulties in generating and detecting high power, continuous wave Terahertz signals. Solid state electronic sources can offer high levels of power in the millimetre wave (up to 300 GHz) range [7] but in the submillimetre wave scale the levels of power that have been reported are low [8]. A technique that takes advantage of the high power millimetre wave sources that can be used for higher frequencies is the frequency multiplication [9]. However, the total efficiency for these sources has yet to be optimised. Another continuous wave source that has shown significant levels of power in the upper Terahertz range is the Quantum Cascade Laser but not operating without cryogenic cooling to reduce phonon scattering [10]. One of the most successful methods of generating continuous wave Terahertz signals at room temperature is photomixing through a very fast mixing element. To date, photomixing in Low – Temperature Grown GaAs has achieved low levels of power [11]. To overcome this limitation the use of ultra – fast photodiodes can lead to efficient, portable and tuneable continuous wave Terahertz emitters.

2. Concept of Travelling – Wave Uni – Travelling Carrier (TW-UTC) Photodiode

Two main frequency limitations are inherent in standard p-i-n vertically illuminated photodiodes: i) the transit time limitation and ii) the RC constant time limitation. In p-i-n photodiodes where the process of photon absorption takes place in the depleted region, both electrons and holes contribute to the transit time. Additionally, the RC time constant arises from the lumped nature of vertically illuminated photodiodes imposing an upper limit of operation. To overcome these limitations two different techniques have been proposed: a) the Uni-Travelling Carrier Photodiode [12] and b) the Travelling-Wave photodiode [13]. The former is a photodetection structure (figure 1a) where photon absorption takes place in the p-doped layer. Therefore, holes are majority carriers and the transit time does not depend on the slower hole transport.

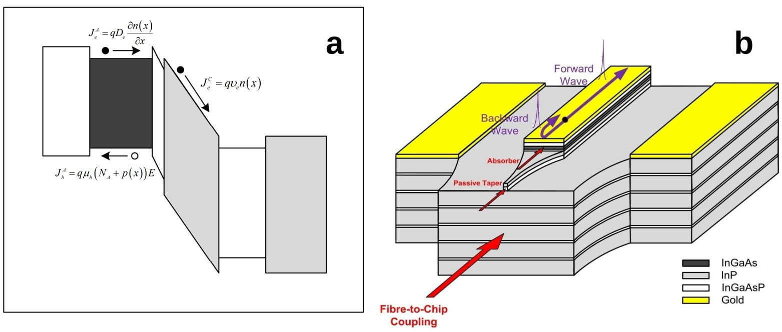

Figure 1: a) Band Structure of a Uni-Travelling Carrier Photodiode b) Travelling Wave Photodiode integrated with a taper waveguide for efficient fibre-to-chip coupling

On the other hand, to overcome the RC time constant the Travelling Wave Photodetector can be employed (figure 1b). In this case, the optical and the electrical signals co-propagate in the same direction. The bandwidth of such a device depends strongly on the matching between the optical group and the electrical phase velocity. The final device, emerging from the combination of the two aforementioned structures, can achieve an improved frequency response by designing the epitaxial structure that mainly affects the transport properties and the geometry of the device to achieve travelling wave conditions. To further enhance the performance of the device in terms of saturation power and responsivity, an efficient technique to couple the optical signal into the device is also of great importance.

3. Optical Design

To take full advantage of the increased saturation power stemming from the travelling wave design, a mode converter has to be integrated with the travelling wave design in order to optimise the responsivity of the device. This type of waveguide converts the mode from a single mode fibre to the modes of a ridge waveguide device with dimensions typically ranging from 2-4 μm for the width and below 150 nm for the thickness of the absorption layer. Figure 2 shows the equivalent problem for the case of a 8 μm wide diluted waveguide coupling into a 3μm wide device with a 70 nm thick absorber.

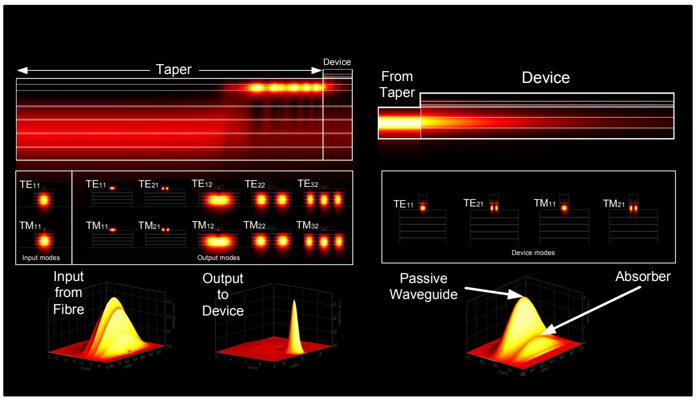

Figure 2: Evanescent coupling from a diluted waveguide into a TW-UTC through a secondary 300 nm InGaAsP waveguide.

The optical signal from the diluted waveguide is coupled into the device absorber through a 300 nm InGaAsP passive waveguide that is used as an intermediate step for mode conversion. This mode converter was implemented into a TW-UTC device and an improved responsivity of 0.3 A/W has been achieved while the calculated limit was 0.4 A/W.

4. Electrical Design

To design the combined Travelling-Wave Uni-Travelling Carrier Photodiode a hybrid Transmission Line model can be used that originally was proposed to model Travelling-Wave photodetectors [13]. The transit time term of the photocurrent according to the Uni-Travelling Carrier Photodiode theory [12] is given by:

$$\tau = \frac{W_A^2}{3D_e} + \frac{W_A}{\upsilon_{th}} \tag{1}$$

where W_A is the absorber thickness, D_e the minority diffusion coefficient and υ_{th} the thermal velocity. The photocurrent term that describes the travelling wave effects is well described by the transmission line model and is given by:

$$I_{TL}(\omega) = C\frac{1}{1+j\omega\tau}\frac{2Z_L}{Z_L\left(1-\exp\left(j\gamma_e l\right)\right)+Z_0\left(1+\exp\left(j\gamma_e l\right)\right)}\left(\frac{\exp\left(-\gamma_e l\right)-\exp\left(-\gamma_o l\right)}{\gamma_o-\gamma_e}+\frac{\exp\left(-\gamma_e l\right)-\exp\left(-(\gamma_o+2\gamma_e)l\right)}{\gamma_o+\gamma_e}\right) \tag{2}$$

where C constant obtained from boundary conditions, Z_L the load impedance (50 Ω), Z_0 the characteristic impedance of the device, l the length of the device, γ_e the electrical propagation constant and γ_o the optical propagation constant. The electrical propagation parameters of the Transmission Line model for a device with a 70 nm absorber (10^{-18} cm^{-3}) and a 300 nm depletion layer were calculated up to 2 THz and shown in figure 3 for different ridge widths:

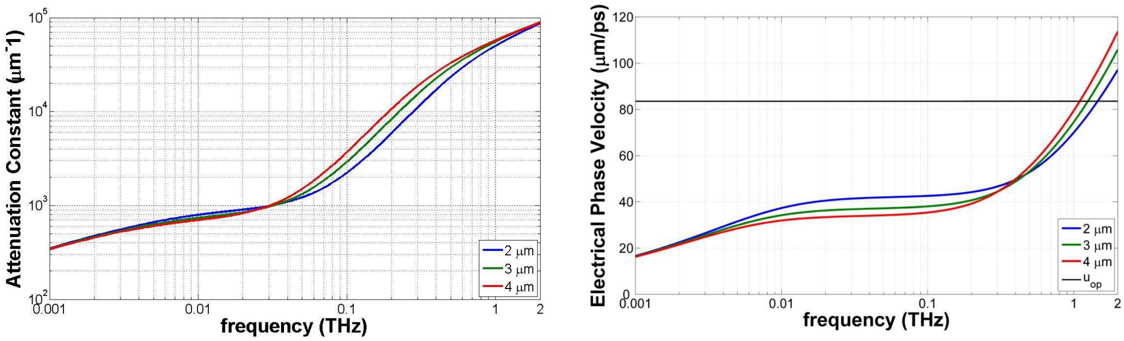

Figure 3: Attenuation constant and electrical phase velocity for 3 different widths of the ridge (2,3 and 4 μm)

From the above it can be seen that the limiting factor at high frequencies can also be the electrical attenuation, while optimum results are obtained with the narrower ridge. On can also notice that true velocity matching is only obtained around 1 THz in such structure. This calculation results can be used to extract the expected frequency response of the TW-UTC photodetector and to compare the advantage from this structure the frequency response of a vertically illuminated device has also been simulated. Both devices had the same epitaxial structure and the same total area (Same RC limited response). In figure 4 the advantage of the travelling wave design was found to be close to 10 dB above 1 THz, while the 3 dB bandwidth was improved from 104 GHz to about 300 GHz.

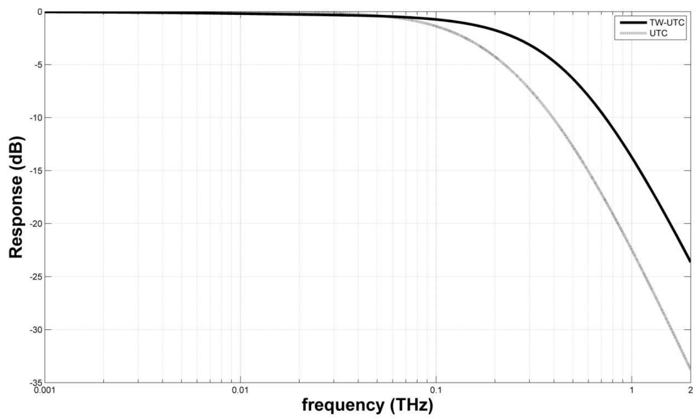

Figure 4: A comparison between a Travelling Wave and a vertically illuminated UTC with the same epitaxial layer and the same area.

5. Conclusions

A novel photodetector design with substantially improved transport and electrical properties has been developed to allow for the optical heterodyne generation of Terahertz signals [14]. Simulations of an optimised structure in terms of responsivity and frequency response have shown significant potential improvement compared to standard devices. Current experimental work on this design is expected to yield high power signal at THz frequencies.

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