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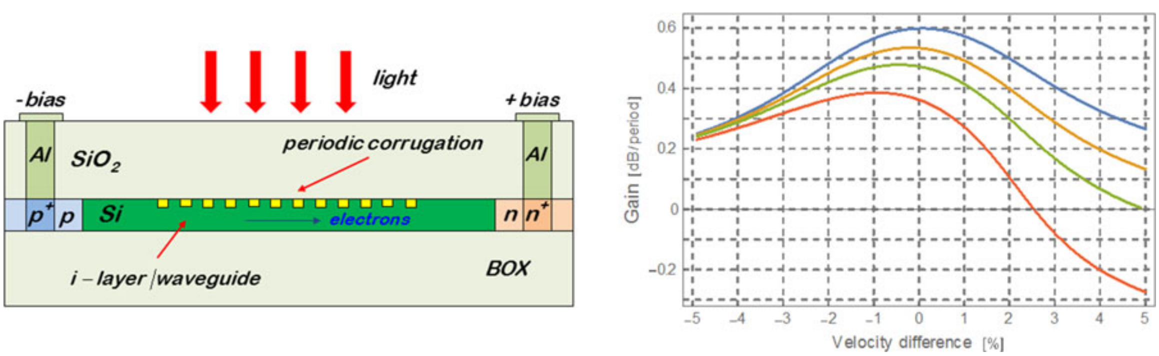

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Design of a New Terahertz Nanowaveguide Amplifier

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Abstract: A novel amplifier is proposed based on a nanostructured waveguide supporting terahertz waves. A lateral pin photodiode structure, biased with a dc voltage and illuminated by a continuous-wave light, serves as an amplifying medium whereby drifting light-generated electrons provide energy required for amplification. Interaction between the propagating terahertz guided wave and the drifting electron stream is analyzed, and a dispersion equation is derived. Real life parameters of silicon are used to demonstrate and illustrate the achievable performance. Doubling of the wave power over only one micrometer is shown to be feasible even when all loss mechanisms are considered.

Index Terms: Waves, optoelectronics, nanophotonics, plasmonics, terahertz waves, periodic structures.

1. Introduction

Considering an electron gas in a conducting medium of an interface with a dielectric as moving due to an applied electrostatic field was analyzed while dispersion of the plasmonic behaviour at such an interface was investigated realizing that the electron gas moving at an average constant velocity is compressible [1]. Electrons compressibility actually describes the ability of an electron stream to bunch as a result of its interaction with a propagating wave.

The attractiveness in studying this type of interaction stems from the known fact that an accelerating electron beam can amplify an electromagnetic wave traveling along it [2]. Solid-state versions of possible embodiments were also proposed [3]. A periodic structure guiding a light wave and interacting with a free-space electron beam was considered in [4] and studied in more detail in [5].

In this letter we focus on the amplification potential of a compressible electron ensemble that is moving under the effect of an applied electric field inside a material. We consider a solid-state configuration whereby a free-charge-depleted semiconductor acts as a medium to conduct electrons excited by an incident light, as well as a waveguide. An interaction between the drifting electrons and terahertz waves is analyzed. The basic derivation of the dispersion equation for this case is performed and is in a qualitative agreement with that in [6]. A more comprehensive literature review of this subject can be found in [1] and there in.

2. Theory

A one-dimensional case of moving electrons along the z-direction is considered for simplicity but without a loss of general understanding. The derivation uses Maxwell's equations solved for propagating waves, the relationship between the velocity and the fields, i.e. the Lorentz force law, and the relation between the electric field and the current density, i.e. the continuity equation. The electric field generating a current in the electron stream is found in this case, similar to expressions in [2], as [1]:

$$J_z = i\frac{\varepsilon_0\,\omega_p^2\,\omega}{(\omega-\beta\,v_d+i\gamma)\,(\omega-\beta\,v_d)}E_z \tag{1}$$

where E_z is the electric field, J_z is the current density, ω is the angular frequency, β is the propagation constant, v_d is the average drift velocity, γ is damping, ε_0 is the permittivity of vacuum, and $\omega_p = e\sqrt{\frac{N}{m\,\varepsilon_0}}$ is the plasma frequency in vacuum with e, N, m being the electron charge, carrier density, and electron mass in the semiconductor that includes its effective mass, respectively. The effect of the background permittivity of the semiconductor has been taken into account during the derivation as shown below in (3).

Current modulation on the electron beam excites a wave in a guide which in turn modulates the beam, and the process continues along the structure. Thus the current density, in turn, produces an electric field that can be found in the form, similar to the one in [6] whereby the current elements of the total current are integrated over their region to yield corresponding electric fields as dictated by Maxwell's equations:

$$E_z = -2K\,\frac{\beta_0}{i\left(\beta^2-\beta_0^2\right)}J_z \tag{2}$$

where β_0 is the propagation constant of a natural mode in the waveguide, and K is the normalization constant related to the total power carried. Combining equations (1) and (2) yields a dispersion relation in a normalized form as:

$$\sqrt{\varepsilon_\infty}(\Omega-B\,\Delta)\,(\Omega-B\,\Delta+i\,\Gamma)\left[(\Omega+i\,A\,\Delta_0)^2-B^2{\Delta_0}^2\right] - \Omega\,\Delta_0(\Omega+i\,A\,\Delta_0)=0. \tag{3}$$

Here all parameters are normalized to the plasma frequency, ω_p, and the speed of light, c. Ω is the frequency, B is the complex propagation constant, Δ is the drift velocity, Γ is the electron collision loss, A is the transmission loss of the waveguide mode, Δ_0 is the velocity of a natural waveguide mode, and ε_∞ is the background permittivity of the semiconductor.

As an embodiment of the presented idea, a structure of the lateral pin photodiode is considered with one boundary having periodic grooves to support a waveguide mode with a velocity close to the electron drift velocity. Under reverse bias the depletion layer between the contacts is free of charges. When light is incident on the structure, generated free electrons will drift towards the positive terminal. For a sufficiently high reverse bias the electrons will drift at the saturated velocity that will be close to that of the chosen waveguide mode; in fact slightly higher, which is a condition for amplification [6]. The details of the actual structure design will be available in [7].

A schematic cross-sectional view is shown here in Fig. 1. It is basically very similar to the one reported with experimental results as a lateral pin photodiode [8]. The proposed structure is compatible with the standard CMOS process whereby it is designed to employ a silicon-on-insulator (SOI) substrate with a silicon absorption layer. The indicated corrugation along the intrinsic layer serves as a terahertz periodic waveguide that supports the desired amplified frequency. The intrinsic layer is the main light absorbing region where the light-generated carriers quickly drift under the influence of a strong internal electric field provided by a reverse bias, as in any pin photodiode [9].

Moving carriers exchange their kinetic energy with an electromagnetic wave that, under certain conditions of phase matching, gets amplified, via a similar interaction as in electron tubes [11]. It should be noted that consideration of holes drifting in the opposite direction can be conveniently

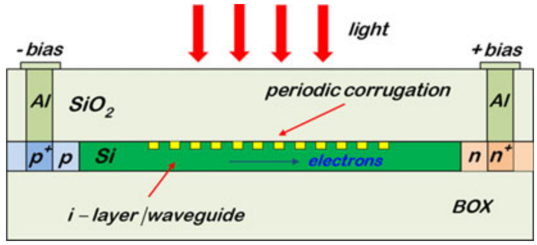

Fig. 1. Schematic diagram of proposed THz amplifier structure compatible with standard SOI CMOS process.

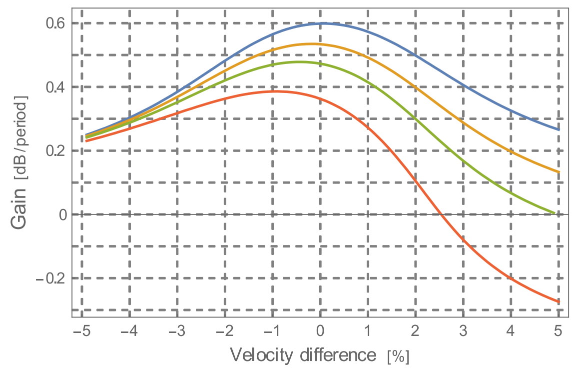

Fig. 2. Gain per period as function of velocity difference. Transmission loss $\alpha_T = 0$ (blue), 3×10^2 cm^{-1} (orange), 6×10^2 cm^{-1} (green), 12×10^2 cm^{-1} (red).

included in the analysis and, in principle, same results are obtained without losing the general validity of results presented here.

3. Numerical Results

Fig. 2 shows gain of the wave in dB per wave's period for several different transmission losses in the waveguide and including the electron stream collision loss. The horizontal axis is the ratio of the velocities of the electrons drift and that of the waveguide mode. A frequency below the plasma frequency is used so the free carrier absorption can be neglected [9]. A realistic drift velocity of 10^7 cm/s is considered that is, for example, a typical value for silicon [10]. The mode loss is around 1000 cm^{-1}, which is quite a conservative value.

The plots in Fig. 2 were obtained from the solutions to (3) for the normalized complex propagation constant B as a function of the normalized velocity Δ. Since the imaginary parts of the de-normalized complex propagation constant β represent the actual gain/loss of the THz wave and the real parts determine its velocity, Fig. 2 shows such dependence as a function of the average electron velocity v_d difference with respect to the wave velocity.

One can see in the figure that as the transmission loss increases, the gain drops and can even become negative. Another interesting, and to be expected, feature demonstrated here is that the maximum of gain shifts towards negative percentage with an increase in the transmission loss. This proves the known fact [10] that the amplifying wave travels slightly slower than the electron stream that is providing the wave with energy to grow.

For illustration, silicon parameters were used to estimate some achievable gain and other practical parameters. Tables 1, 2 and 3 summarize the values that were obtained after de-normalization of the generic data obtained from the normalized dispersion equation. Table 1 contains basic properties of silicon as known in literature and selected to match the calculations here [10].

Table 2 summarizes the values of design parameters chosen. Terahertz region is of interest here; realistic practical values have been selected.

TABLE 1
Silicon Parameters Used

Symbol	Quantity	Values
ε_∞	Background permittivity	11.7
m^*	Effective electron mass	0.26 m_0
α	Absorption coefficient	10^4 cm^{-1}
γ	Damping coefficient	5.6×10^{12} s^{-1}
μ_e	Electron mobility	1200 cm V^{-1} s^{-1}

TABLE 2
Parameters of the Amplifier Structure

Symbol	Quantity	Values
$\omega_p/2\pi$	Plasma frequency	3 THz
$\omega_{op}/2\pi$	Operating frequency	2 THz
α_T	Transmission loss	10^2–10^3 cm^{-1}
N	Electron concentration	3×10^{16} cm^{-3}
V_w	Waveguide volume	$1 \times 1 \times 1$ μm^3
P_{in}	Incident optical power	5 dBm

TABLE 3
Achievable Performance of a Terahertz Amplifier Structure

		Transmission loss		
Symbol	Quantity	0	10^2 cm^{-1}	10^3 cm^{-1}
l_p [nm]	Wave period	48.7	48.6	48.4
g_{lp} [dB]	Gain per period	0.6	0.48	0.39
g_{lw} [dB]	Waveguide gain	12.3	10.2	8

Table 3 shows the solutions to the dispersion equation for the terahertz waveguide amplifier with given parameters. One can see that even for quite high transmission losses and including the high damping losses (electron collisions), an appreciable gain of 8 dB is still achieved for just a one-micrometer long waveguide. It means that the terahertz mode power would more than double over such a short length with a voltage of only one volt.

4. Practical Considerations

Lateral photodiode structures have been known, studied, fabricated and tested in the past [12]. The CMOS technology is suitable for their implementation [13] and has proven to be compatible, effective, and useful in practical devices. Combining a lateral pin photodiode with a periodic structure, for example a photonic nanocrystal, has also been shown to be feasible technologically and practically [14]. Therefore, our proposed structure is compatible with an industry standard of the silicon CMOS technological processing [15].

Another practical issue to consider is coupling the THz signal out of our designed amplifying structure. It is a fundamental problem not only with our design but generally with periodic structures and photonic crystals [16] whereby the physical features are much smaller than the free-space wavelength of electromagnetic waves involved in the interaction. It is certainly a challenging problem to investigate; however, it is well beyond the scope of this paper to address such a task.

5. Conclusion

A novel terahertz waveguide amplifier has been proposed and analyzed. A lateral pin photodiode structure, biased with a dc voltage and illuminated by a continuous-wave light, serves as an amplifying waveguide. Energy of drifting light-generated electrons is exploited to produce an increasing terahertz guided wave. Real life parameters of silicon and a corresponding realistic nanostructure have been used to simulate the performance of the amplifier. An appreciable gain of the wave has been obtained. A promising application potential of such a structure is practically feasible.

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