Optically Controlled Spatial Modulation of (Sub-)Millimeter Waves Using *nipi*-Doped Semiconductors

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***Abstract*—The use of a molecular beam epitaxy engineered semiconductor structure to quasioptically modulate a millimeter wave Gaussian beam using an optical control signal has been demonstrated. The RF transmission is modulated spatially by the optically generated excess carrier density. Low optical intensities are sufficient due to the long recombination lifetime achieved in the *nipi*-doped structure used. A modulation depth of more than 15 dB in transmission mode has been obtained at 100 GHz. Modulation has been measured up to 5 THz using a Fourier transform spectrometer.**

I. Introduction

OPTOELECTRONIC techniques to control microwaves in waveguides and transmission line systems are not new [1], [2] and are still under development [3]. The control of millimeter waves in guided wave systems, however, poses some problems inherent to higher frequencies (greater losses, smaller physical dimensions, proper matching, higher manufacturing costs, etc.). Therefore, most of the signal handling in the (sub-) millimeter wave (SMMW) range is done quasioptically.

In this letter we demonstrate the use of an InGaAs/GaAs *nipi*-doped multiple quantum well (MQW) structure for efficient optical control of a SMMW Gaussian beam in a quasioptical system. Previous experiments have demonstrated the feasibility of this technique [4]–[6].

The principle used is the generation of an excess carrier density through optical excitation, this modifies the conductivity of the semiconductor with a subsequent change in the optical properties.

By using the complex conductivity of an imperfect dielectric we can obtain an expression for its complex relative permittivity of the form

$$\tilde{\varepsilon}_r(N_e,\omega) = \varepsilon_r + \omega_p^2\left\langle \frac{\tau_m^2}{1+(\omega\tau_m)^2}\right\rangle - j\frac{\omega_p^2}{\omega}\left\langle \frac{\tau_m}{1+(\omega\tau_m)^2}\right\rangle \quad (1)$$

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where ε_r is the relative permittivity of the base material, τ_m is the momentum relaxation time, ω is the SMMW angular frequency and ω_p is the plasma frequency defined as

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e^*}} \quad (2)$$

with N_e the excess carrier density, ε_0 the free space permittivity, e the electron charge, and m_e^* the effective electron mass. Equation (1) is valid provided that only electrons contribute to the conductivity. This is a good approximation in GaAs since the hole mobility is nearly 20 times lower than that for electrons.

The complex dielectric constant defined by (1) has real and imaginary components that will produce a phase shift and an attenuation respectively, for a propagating SMMW. For frequencies above the plasma frequency the imaginary part of the permitivitty will vanish and the material will become "transparent."

The reflection and transmission coefficients for an electromagnetic wave incident on a layered dielectric medium are functions of the refractive indexes of the different layers, and these in turn are defined as the square roots of the respective relative permittivities. Most significant for quasioptical modulation of SMMW is that, for a fixed frequency, the relative dielectric constant will only be function of the excess carrier density N_e thus the photogenerated free carriers changes the active region from a nearly lossless dielectric into an imperfect mirror.

II. Semiconductor Structure

The material studied is an engineered semiconductor heterostructure optimized for optically controlled optical modulation [8]. The structure is grown by molecular beam epitaxy (MBE), and consists of 44 $In_{0.2}Ga_{0.8}As$ quantum wells (QW), each 6.5 nm thick, separated by 78-nm-thick GaAs barriers. In the center of each GaAs barrier a Be-doping plane (p-type) with a sheet density of $9\cdot10^{12}$ cm^{-2} is inserted. On both sides of the QW's, using 10-nm-thick spacer layers, Si-doping planes (n-type) with sheet densities of $3\cdot 10^{12}$ cm^{-2} are inserted. This results in an excess free hole density under thermal equilibrium.

Under photoinduced electron-hole pair generation, electrons will be attracted to the QW's and the holes to the barrier region

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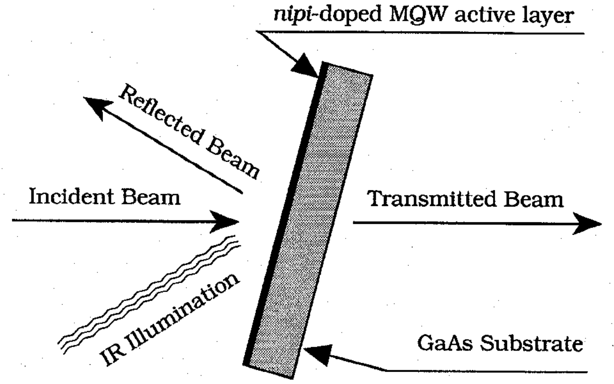

Fig. 1. Optical control of a (sub-)millimeter wave Gaussian beam in transmission mode.

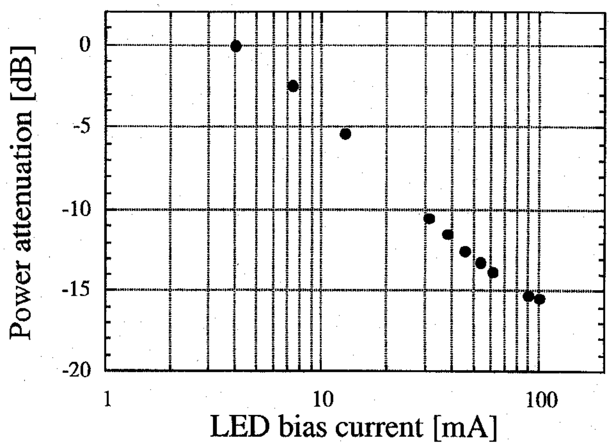

Fig. 2. Measured attenuation of RF power at 100 GHz as a function of IR LED bias current.

midway between the wells, resulting in their spatial separation. This spatial separation of carriers reduce the recombination rate and thus a large increase in the density of free carriers can be established using low optical excitation intensities. This facilitates efficient modulation of SMMW's using low optical control intensities.

The structure has been described elsewhere, as well as its main properties for modulation in the near infrared [7], [8].

III. Experimental Setup

A simplified scheme for the measurement setup can be seen in Fig. 1: the incident SMMW beam is impinging over the *nipi*-doped structure with part of it being transmitted and part reflected. At the same time we shine IR light over the material in order to modulate the excess carrier density.

The infrared (IR) control signal is produced by a commercially available LED (Texas Instruments TIL 31B, 6 mW typical output power @ 100 mA, $\lambda = 940$ nm). The geometry of the LED mounting is such that it creates a Gaussian light spot with a full width at half maximum of about 2 mm, yielding a maximum optical intensity on the order of 40 mW/cm^2 for 100-mA drive current.

The millimeter wavelength measurements (100 GHz) are performed in an optical bench with an IMPATT diode as the source. The oscillator is coupled through a corrugated horn and focused with a lens on the material, creating a Gaussian beam

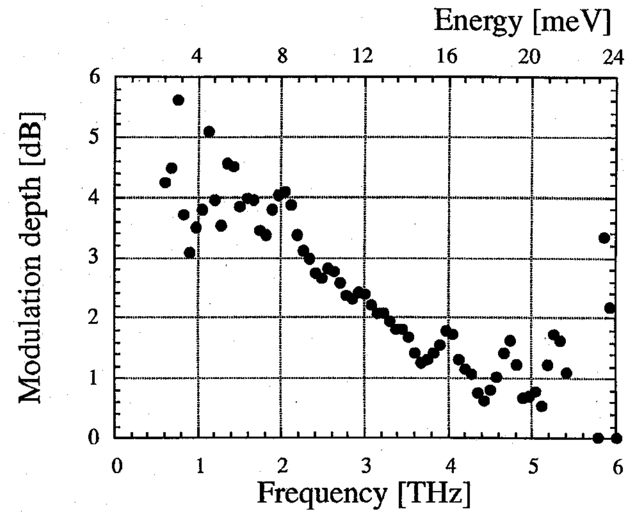

Fig. 3. Modulation depth in transmission mode for a *nipi* MQW heterostructure between 0.5 and 6 THz.

with a waist radius of about 5 mm at the wafer. The transmitted power is detected using a total power detector coupled through a corrugated horn.

For the sub-millimeter measurements we use a Fourier transform spectrometer (FTS), extending the measurements to the 0.5–8 THz range [5]. The geometry of the IR illumination is the same as for the millimeter wave measurements.

IV. Modulation and Insertion Loss

Fig. 2 is a plot of the transmitted RF power, at 100 GHz, versus the LED bias current. We know, from the data of this LED, that the IR output power increases linearly with bias current. Therefore this graph shows the transmitted RF power versus optical power incident on the material.

The RF attenuation versus illumination curve is not linear, showing a logarithmic saturation effect, still, the dynamic range is more than 15 dB. The main point here is the capability of a nearly linear control of the attenuation with the IR power illuminating the material.

The measured insertion loss is 0.5 dB. This low loss can be explained by interferometric effects at this frequency since the GaAs substrate has a thickness close to $\lambda/2$ ($\sim$400 μm) in the material at 100 GHz. The substrate thickness can effectively be used to optimize the modulation depth and insertion loss [6].

The results of the measurement in the higher frequency range are summarized in Figs. 3 and 4 for the transmission case. In Fig. 3 the modulation depth is plotted for frequencies between 0.5 and 6 THz. The modulation depth is determined by switching between no IR illumination and full available IR power (40 mW/cm^2).

By using relation (2) for the plasma frequency value, and an estimated free carrier density of $N_e = 10^{17}$ cm^{-3} [8], we find that the plasma frequency is on the order of a few THz. This is the most probable cause for the decrease in modulation depth in the higher frequency range since the material becomes transparent.

The insertion loss is shown in Fig. 4. In the frequency range where the device has a relatively large modulation depth (0.5–2.5 THz), the losses are on the order of 5–6 dB, being

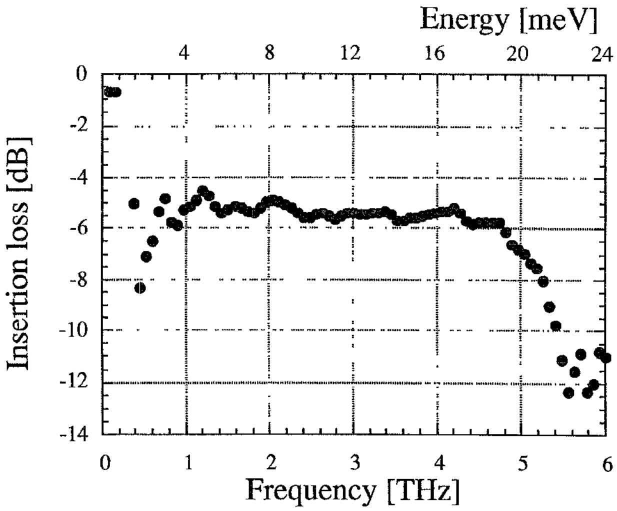

Fig. 4. Insertion loss in transmission mode for a *nipi* MQW heterostructure between 0.5 and 6 THz.

rather flat over the frequency range between 1 and 5 THz. At frequencies over 5 THz the substrate presents too high losses to be of any practical use.

The losses in the higher frequency range are inherent to the semi-insulating GaAs substrate used to grow the *nipi* heterostructure. This has been confirmed by insertion loss measurements on a plain substrate.

V. Diffusion Length and Effective Carrier Lifetime

Once determined that the material is suitable for modulation of a SMMW Gaussian beam, two important parameters to characterize are the diffusion length and the effective lifetime of the photogenerated carriers, since they determine the spatial resolution of the modulation and the modulation speed, respectively.

The diffusion length is determined by mapping the RF modulation across the surface of the material using a waveguide probe mounted on an X-Y mapper as a scanning element. This yields an estimated diffusion length on the order of 1 mm [6].

Rich *et al.* [10] have measured the diffusion length and the carrier lifetime of this type of material, at different temperatures, and have found a diffusion anisotropy caused by strain induced misfit dislocations in the lattice mismatched material. Their results at room temperature give an average diffusion length of 1.4 mm that compares very well with the value obtained in our measurements.

The lifetime is measured using the same setup as for the diffusion length, but now using a lock-in amplifier to measure the transmitted millimeter wave power as a function of the frequency at which the LED is modulated. Following Ando *et al.* [11] the effective carrier lifetime is determined to be on the order of 80 ms [6]. This also compares favorably with previous measurements [8].

VI. Discussion and Conclusion

We have demonstrated the use of a *nipi*-doped InGaAs/GaAs MQW structure for optically controlled spatial modulation of a SMMW Gaussian beam in a quasioptic system. The RF attenuation is found to vary linearly with IR illumination power, and the estimated lateral carrier diffusion length renders the studied material a strong candidate for spatial modulation of SMMW Gaussian beams.

With a low power optical control signal (~40 mW/cm^2) we can achieve 15-dB transmission modulation of a millimeter wave beam at 100 GHz. The measured insertion loss is on the order of 0.5 dB for this case.

The lateral diffusion length is estimated to be of the order of 1 mm, sufficiently small to allow spatial modulation of SMMW beams. One potential application for this result is the spatial power control of the LO oscillator signal injected quasioptically in the mixer array of a millimeter wave imaging receiver [12].

The long effective lifetime of the carriers (80 ms) limits the modulation speed of the RF Gaussian beam, but is still sufficient to allow the use of this material even as a solid-state beam-chopper for quasioptical synchronous detection schemes.

The device yields optically controlled modulation up to 5 THz and the dynamic range is better than 3 dB up to 2.5 THz in transmission mode. The losses found between 0.5 and 5 THz are moderately large and can be lowered by, for example, reducing the thickness of the GaAs substrate.

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