Generation of Ultrashort Electrical Pulses in Semiconductor Waveguides

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***Abstract*—In this letter, we report a novel device capable of generating ultrashort electrical pulses on a coplanar waveguide (CPW) by means of optical rectification. The device consists of a completely passive GaAs-based optical waveguide, which is velocity matched to a CPW line. Optical pulses are injected into the device and electrical pulses are collected at the output. Experimental results obtained in the laboratory show the potential of this device for high speed optical-to-electrical conversion.**

***Index Terms*—Coplanar waveguides (CPW), electromagnetic propagation, nonlinear optics, optical pulses, optical waveguides, optoelectronic devices.**

I. Introduction

THE GENERATION of an ultrashort electrical pulse from a short optical pulse is of interest in the field of optoelectronics as a potential method for realizing direct optical to microwave conversion. This area is receiving an increasing amount of attention because it represents the important interface between the optical backbone and wirelesss communications. In addition to applications in telecommunications, short electrical pulses have applications as a characterization tool for coplanar transmission lines and integrated devices such as high speed metal–oxide semiconductor transistors. In these applications, an ultrashort electrical pulse propagating along a transmission line is required. The two most common methods of producing such ultrashort electrical pulses are via photoconductivity [1] and optical rectification [2]. The width of the electrical pulse generated by a photoconductive switch is limited by the recombination time of the photogenerated carriers in the material. Subpicosecond pulses can be generated by biasing a transmission line (usually with a voltage of around 5 V) and illuminating a photoconductive gap with a femto-second laser pulse at a wavelength, which coincides with the absorption of the substrate material. However, using optical rectification, the electrical pulse can be generated in a completely passive device and the width of the pulse is limited only by the duration of the optical excitation pulse. Once the ultrashort electrical pulse is generated, it has to propagate on a transmission line. The pulse can be seriously distorted and attenuated while traveling on the transmission line, and therefore, a velocity-matched structure is needed to minimize this.

In this letter, we will describe the results obtained from a novel device specifically designed to generate ultrashort electrical pulses using optical rectification at an input wavelength in the 1.55-μm telecommunications window. In Section II, the basis of optical rectification is outlined. Section III explains the design concept of the device while the experimental setup, results, and conclusions are discussed in Sections IV–VI respectively.

II. Optical Rectification

Optical rectification is a second-order nonlinear phenomenon that generates a dc polarization from an optical wave through the term $\omega - \omega = 0$. The effect results from the second-order nonlinear tensor which is also responsible for second harmonic generation, $\omega + \omega = 2\omega$. GaAs is a well-known nonlinear material; it has a large nonlinear coefficient $\chi^2 = 238$ pm/V at 1.548 μm [3]. Optical rectification can be obtained even if the material has not been phase matched. If an ultrashort optical pulse passes through the crystal, an optical rectification polarization is created in the media. This polarization will have the same time dependence as the optical pulse, and therefore, if it can be coupled into a transmission line, an electromagnetic pulse will be created with a temporal resolution dictated by the duration of the optical pulse. A complete theoretical analysis of optical rectification on GaAs waveguides can be found in [4].

III. Device Description

The optical rectification-effect (ORE) device used in this work was a planar device consisting of an optical ridge waveguide and an electrical coplanar waveguide (CPW). The CPW line was deposited on top of the optical structure and isolated by buffer layer of SiO_2. The central conductor of the CPW line was carefully aligned on top of the ridge with the ground electrodes in close proximity in order to maximize the overlap between the optical and the microwave modes. The ground electrodes of the CPW line are periodically loaded to create a traveling wave device where the phase velocity of the electrical signal is matched to the group velocity of the optical signal. Guidelines for the design and characterization of slow-wave

Manuscript received August 5, 2002; revised November 22, 2002. The work of V. Loyo-Maldonado was supported by the National Council for Science and Technology (CONACyT), Mexico.

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Digital Object Identifier 10.1109/LPT.2002.807898

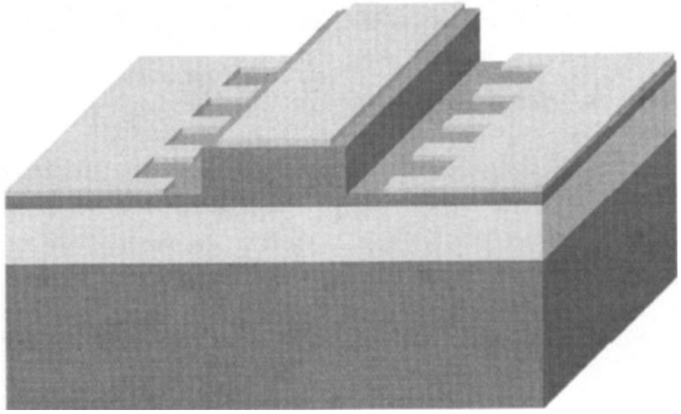

Fig. 1. Schematic of an ORE device. The central conductor of the CPW line is aligned on top of the optical waveguide. The ground electrodes are periodically loaded to create a traveling wave ORE device.

electrodes in GaAs can be found in [5]. A schematic of the ORE device is shown in Fig. 1.

The optical waveguide structure consists of a 1.5-μm-thick $Al_{0.18}Ga_{0.82}As$ core layer sandwiched between a 4-μm $Al_{0.24}Ga_{0.76}As$ lower cladding layer and a 1-μm $Al_{0.24}Ga_{0.76}As$ upper cladding. The epilayers were grown by molecular beam epitaxy on a 3-in diameter semiinsulating GaAs (SI–GaAs) substrate and the ridge structure was defined by standard e-beam lithography techniques. E-beam lithography was used to allow accurate alignment of the electrodes and to achieve precise definition of the slow-wave electrodes needed for a velocity-matched structure. The 5-μm-wide optical ridge was etched down using a $SiCl_4$ process using an Oxford Plasma Technology RIE-80 machine. The optical refractive index of the structure η_{opt} was calculated to be 3.33, using a two-dimensional mode solver.

A 200-nm-SiO_2 layer was deposited on top of the optical structure to reduce the optical loss produced by the leakage of the optical mode into the metal electrodes. The NiCr–Au electrodes forming the CPW line were evaporated and defined using liftoff. The central conductor of the CPW line was 4 μm wide and the gap between the signal and ground electrodes was 3 μm. The CPW electrodes were tapered out to allow probing the structure with a high-frequency probe. Modeling of the slow-wave electrodes was carried out using Microwave Office and confirmed experimentally using a microwave probe station and a HP8510 network analyzer. The s-parameters of the lines were measured from 0 to 60 GHz. These parameters were then used to calculate the ABCD matrix from which the characteristic impedance Z_0 and microwave refractive index η_{mw} were extracted. The characteristic values of the CPW were $Z_0 = 65\ \Omega$ and $\eta_{\mathrm{mw}} = 3.2$.

Even when the design of the CPW line was aimed to match η_{opt}, a slight discrepancy between η_{opt} and η_{mw} exists. This can be attributed to the accuracy of the simulation and the accuracy of the line impedance used for calibration. The propagation loss α of the ORE device was measured using the Fabry–Pérot method and a value of $\alpha = 1.8$ dB/cm was obtained. This is a low value considering the close proximity of the metal electrodes to the optical structure. The detailed steps of the fabrication process have been discussed previously in [6].

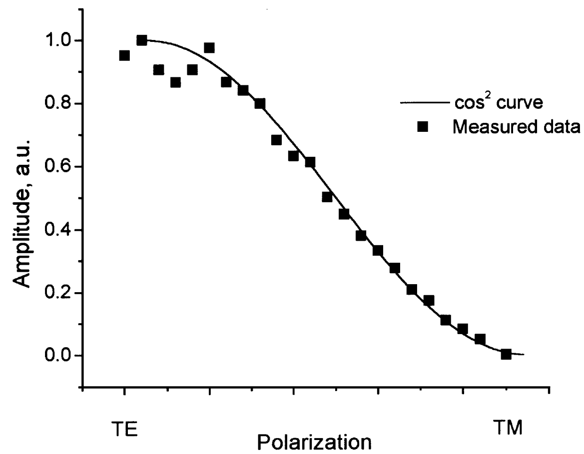

Fig. 2. Polarization dependence of the electrical signal. The solid squares are experimental points taken for different input polarization states. The signal presents $\cos^2$ behavior (solid curve) typical of optical rectification.

IV. Experimental Setup

The experimental setup can be described as follows: The optical source used in the experiment was an optical parametric oscillator (OPO) with a repetition rate of 86.7 MHz and a pulsewidth of 250 fs, full-width at half-maximum (FWHM). The OPO could be tuned from 1480 to 1580 nm using the signal output. An average power of 30 mW could be maintained over the whole wavelength range. The beam from the OPO was end-fire coupled into the ORE device using a $\times$40-microscope objective and, the light at the output of the device was collected using a $\times$20-microscope objective and projected onto a charged-coupled device camera to help with the alignment. A $\lambda/2$ plate was positioned on the optical path before the input lens to manipulate the polarization state going into the device. The polarization direction could be altered continuously from transverse electric (TE) to transvese magnetic (TM) by rotating the $\lambda/2$ plate between 0° and 90°. As explained in Section II, the optical mode traveling on the waveguide induces an electric field in the CPW line by means of the ORE. To detect such a signal, the ORE device was probed using a 40-GHz microwave probe and connected to a microwave spectrum analyzer with a bandwidth of 40 GHz.

V. Results

Keeping the input power constant, the wavelength was swept over the whole working range of the OPO. The presence of electrical pulses propagating in the structure was confirmed by the signal detected by the spectrum analyzer. The fundamental frequency peak was centered at the repetition rate of the laser. The amplitude of the signal was considerably higher for shorter wavelengths, evidence of the two-photon absorption (TPA) tail. At $\lambda = 1580$ nm, the TPA signal is almost completely suppressed; however, there is a small contribution from band tail states which acts as an offset to the ORE signal. The results presented here were obtained using an input wavelength of 1580 nm, where the detrimental effects of multiphoton absorption are minimized [7].

The polarization dependence of the ORE signal is shown in Fig. 2. The solid squares are the experimental points taken for

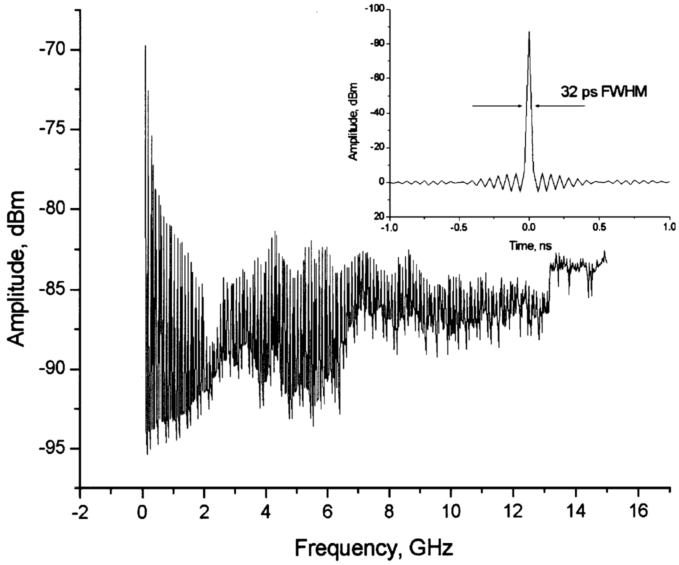

Fig. 3. Frequency spectrum of the electrical signal. The harmonics are spaced 86.7 MHz which corresponds to the repetition rate of the laser. Inset: Frequency spectrum converted into time domain by using FFT.

different input polarization states while the solid line is a $\cos^2$ curve only plotted to help visualize the trend. The electrical signal has a maximum for TE input polarization and minimum for TM input polarization as expected from an ORE signal. The absolute magnitude of the signal for TE polarization was -73 dBm. We believed that velocity-match imperfections within the ORE device and the high loss associated with the transmission line attenuate and disperse the signal, and are the reasons of the weak signal obtained. The fact that the signal is weak does not allow us to connect a sampling oscilloscope and observe the electrical pulse directly. In order to estimate the temporal resolution of the electrical pulses, indirect methods have to be used. An electrical pulse train will generate a number of harmonics determined by the width of the pulse and/or by the bandwidth of the spectrum analyzer. The frequency spectrum of the signal obtained from the ORE device is shown in Fig. 3. If we apply a fast Fourier transform (FFT) algorithm to convert and analyze this signal in the time domain, we find that the spectrum corresponds to a pulse with a width of 32 ps, FWHM. The signal in the time domain can be seen in the inset of Fig. 3. Because there is no phase information in the signal obtained from the spectrum analyzer (Fig. 3), this approximation is only valid in the case where the measurement system is perfect and all the harmonics are affected equally. The temporal resolution of the pulse can be obtained by electrooptic sampling, or by integrating a photoconductive switch on the CPW line.

VI. Conclusion

We have shown the generation of ultrashort electrical pulses in a passive semiconductor waveguide. The device under discussion uses the ORE to convert an optical input signal to an electrical output signal. The analysis of the microwave spectrum of the signal indicates that optical rectification is the mechanism behind the generation of the electrical pulses. The novel device presented therefore shows the potential for optical to microwave conversion.

Acknowledgment

V. Loyo-Maldonado would like to dedicate this letter to the memory of his beloved friend J. R. Benítez-Pérez, a young scientist who passed away in August 2001.

References

[1] D. H. Auston, "Picosecond optoelectronic switching and gating in silicon," *Appl. Phys. Lett.*, vol. 26, no. 3, pp. 101–103, 1975.

[2] A. Nahata and T. F. Heinz, "Generation of subpicosecond electrical pulses by optical rectification," *Opt. Lett.*, vol. 23, pp. 867–869, 1998.

[3] J. B. Khurgin, "Second-order nonlinearities and optical rectification," in *Semiconductors and Semimeals, Nonlinear Optics in Semiconductors II*, D. E. Garmire and A. Kost, Eds. New York: Academic, 1998, vol. 59, pp. 1–82.

[4] U. Peschel, K. Bubke, D. C. Hutchings, J. S. Aitchison, and J. M. Arnold, "Optical rectification in a travelling-wave geometry," *Phys. Rev. A*, vol. 60, pp. 4918–4926, 1999.

[5] R. Spickermann and N. Dagli, "Experimental analysis of millimeter wave coplanar waveguide slow wave structures on GaAs," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1918–1924, Oct. 1994.

[6] V. Loyo-Maldonado, H. K. Lee, T. Lohdi, I. G. Thayne, and J. S. Aitchison, "Design and fabrication of an optical rectification device," in *Proc. Quantum Electronics Photonics*, vol. 15, 2001, p. 169.

[7] J. S. Aitchison, D. C. Hutchings, J. U. Kang, G. I. Stegeman, and A. Villeneuve, "The nonlinear optical properties of AlGaAs at the half band gap," *IEEE J. Quantum Electron.*, vol. 33, pp. 341–348, Mar. 1997.