TRAVELLING-WAVE OPTOELECTRONIC DEVICES FOR MICROWAVE APPLICATIONS

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Abstract - In this paper, we will discuss the fundamental concepts of ultrafast microwave photonic devices based upon the interaction between propagating microwaves and optical signal beams. Such travelling-wave optoelectronic devices utilizing, for example, microstrip or coplanar transmission lines as electrical waveguides exhibit cut-off frequencies not limited by the usual RC time constant. As a result, a high bandwidth together with improved efficiency and power capabilities are expected. In particular, travelling-wave photodetectors, waveguide and vertical electrooptical modulators, microstrip optical switches and coplanar laser diodes are presented. Preliminary experimental results are also discussed.

Introduction - The integration of ultrafast photonic devices operating in the microwave regime is expected to be a key technology in developing future high-speed and high-capacity lightwave systems. The electrical cut-off frequency of photonic devices is usually limited by internal physical time constants and, additionally, by the device structure and the external circuitry. In order to achieve operation up to millimeter wave frequencies, the device dimensions may not exceed a few µm to get a capacitance far below 1pF. Note that a value of 1pF connected to a characteristic impedance of 50Ω leads to a cut-off frequency of merely 3GHz. On the other hand, an electrical contact size of about 100µm can reach the order of a quarter wavelength already at 10GHz when slow mode effects [1] occur. In that case, the device properties depend on travelling wave effects, and no RC time constant can be defined in the usually way. In contrast, wave propagation effects have necessarily to be included in the simulation, modelling and fabrication of such components [2-10].
In this paper, microwave photonic devices are presented, that utilize microstrip or coplanar transmission lines as electrical waveguides. The metallization is formed according to well-known microwave techniques, and the input resistance is determined by the characteristic impedance of the coplanar waveguide. The light can also be guided using conventional optical waveguides, and the optoelectronic conversion takes place via a microwave-optical interaction process in space and time domain.

Coplanar Waveguides - The general outline of a coplanar optoelectronic device is sketched in Fig.1. Electrically, the metallic contacts are used as microwave or millimeterwave transmission lines. The electrical wave propagation is now mainly determined by the multilayered semiconductor substrate material, where the cross section in most cases is that of a pn-, Schottky-, or pin-diode [6]. In other words, the doping levels of the different layers are choosen in such a way that the electric field is concentrated in the active (depletion) layer beneath the center conductor.

Because the magnetic field is not influenced by the conductivity of the layers, slow wave properties will arise, where the slowing factor can be as large as 20 to 100 [1,12]. Optically, the region of the depletion layer, i.e. the active volume, can be used as a waveguide for the

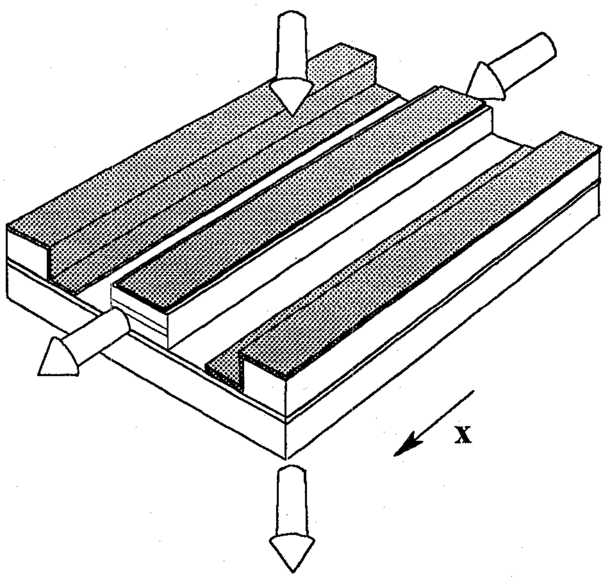

Fig. 1. Sketch of the coplanar optoelectronic device

propagation of light. Here different cases can be distinguished: The optical input energy can be absorbed to generate a microwave signal or the optical beam can be modulated by an electrical, i.e. a microwave signal. The resulting devices are called travelling-wave (TW) photodetector or modulator [3,11-14]. In case of a laser

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diode, light is generated and the optical output is controlled by the microwave signal [15]. Note that a vertical/oblique illumination (photodetector), transmission or reflection (modulator) and emission of light (vertical cavity surface emitting laser), see Fig.1 , can also lead to travelling-wave effects provided that the extension of the optical beam in x-direction exceeds a quarter of the microwave wavelength, approximately.

In Fig. 2, the equivalent circuit for electrical wave propagation on a coplanar transmission line on layered media is shown. Note that *C'* and *G'* are nonlinear elements controlled by the properties of the depletion layer. In case of a photodetector, I'_{ph} is an impressed current source per unit length describing the opto-electric conversion, and here $I'_{ph}=I'_{ph}$ (x,t) is also a wave due to the propagation of light. The circuit in Fig.2 has to be completed by a similar circuit describing the optical domain where the optical losses lead to the value of I'_{ph}. In the case of a travelling-wave modulator, $I'_{ph}=0$ in Fig.2, and the voltage drop V_d can be used to calculate the modulation effect via the electrooptical properties of the active layer, see for example [13]. In the case of laser diodes the nonlinear *G'* of Fig.2 gives rise to an "optical" current source, i.e. the generation of photons.

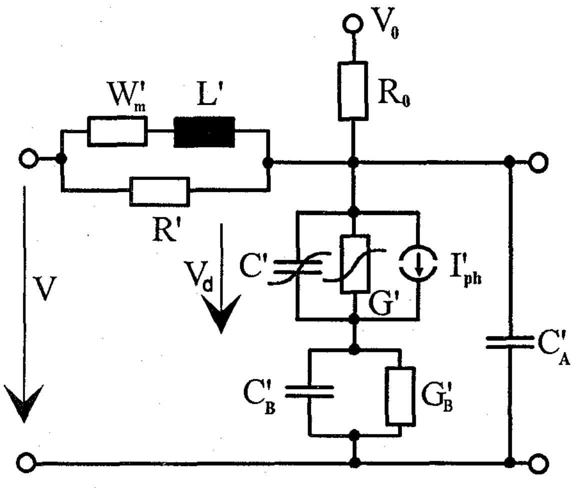

Fig.2 Equivalent circuit for wave propagation in the millimeter wave region [1-8]

In summary, travelling-wave (TW) optoelectronic devices can be described by electrical and optical equivalent circuits, where the interaction is given by elements with a parametric space and time dependence. The efficiency of travelling-wave devices depends critically on the degree of phase matching between the optical and the microwave signal. For the lossless case, wave propagation is determined by L' and C' of the coplanar transmission line. Phase matched conditions can be achieved for identical phase velocities according to

$$v_{opt} = \frac{c_0}{n_{opt}} = \frac{1}{\sqrt{L'C'}} = v_{RF}$$

with the free space light velocity c_0 and the optical index of refraction n_{opt}. For a microwave characteristic impedance of

$$Z_w = \sqrt{\frac{L'}{C'}} = 50\Omega$$

and n_{opt}=3.5 for a III-V semiconductor the inductance per unit length is

$$L' = \frac{Z \cdot n_{opt}}{c_0} = 5.7 nH / cm$$

and the capacitance per unit length is

$$C' = \frac{n_{opt}}{Z \cdot c_0} = 52.3 pF / cm$$

for phase matching. L'and C'can be used to design the coplanar transmission line or, in other cases, the microstrip line.

Travelling-wave photodetector - Fig.3 shows the cross section of a travelling-wave photodetector.

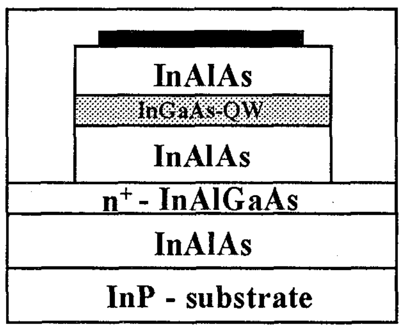

Fig.3. Cross-section of a travelling-wave photodetector

Here the quaternary semiconductor together with the InAlAs cladding layers form the optical waveguide. The InGaAs quantum well is used as an absorbing film where the optical attenuation is due to a leakage effect and the losses can be controlled by several geometrical parameters. Such a photodetector can easily be used to generate microwave power when two optical beams with different frequencies are propagating down the line. As a result of wave mixing effect in the heterodyne photodetector a microwave signal is generated, the frequency of which is given by the difference of the optical frequencies. From numerical simulations it is concluded, that in the case of phase matching the microwave amplitude increases monotonically with distance x and the microwave output signal becomes a maximum. It is foreseen, that such a photodetector can especially be used at high power levels together with a pronounced linearity and an optimum quantum efficiency [16]. The microwave bandwidth is only determined by internal physical parameters. Note also that such a device can be used as an optically controlled microwave modulator, such as a phase shifter, delay line or attenuator.

Travelling-wave modulator - In Fig.4 the cross section of a travelling-wave waveguide modulator is sketched. Experimentally, an nin-electrooptical modulator has been investigated using the quantum confined Stark effect in strained InGaAs/AlGaAs MQW waveguide structures [13]. Experimental results of the electrical bandwidth measured in a common 50Ω system reveal a cut-off frequency in excess of 40GHz due to an optimum impedance and phase matching.

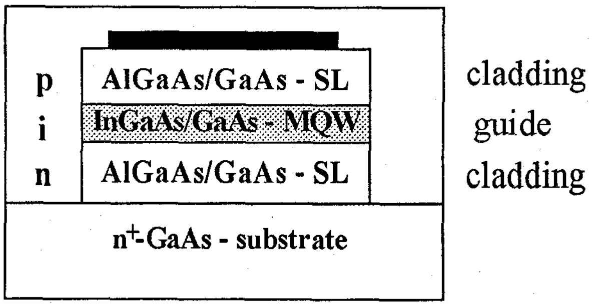

Fig. 4. Cross section of a travelling-wave electrooptical modulator[13]

High-speed vertical modulator - Fig. 5 elucidates the structure of a vertical electrooptical modulator which consists of an active MQW layer sandwitched between two semiconductor Bragg reflectors.

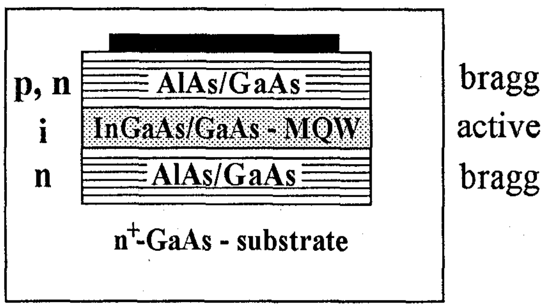

Fig. 5. Cross section of a vertical travelling-wave vertical electrooptical modulator [13].

The most interesting properties of such a device can be traced back to the situation where different parts of the optical beam - in x-direction - experience different amplitude or phase shifts as a result of the propagating microwave. In the special case of a standing microwave the device is the electrooptic analogue to the well-known acousto-optic Bragg deflector / frequency shifter / filter etc. In the case of the coplanar vertical electrooptical modulator, however, a bandwidth of more than 40GHz has been obtained well above any limit of the acoustooptical modulator.

Digital optical switch. - The high-speed digital optical switch, presently under investigation, is sketched in Fig. 6 [17]. The cross section is that of Fig. 4.

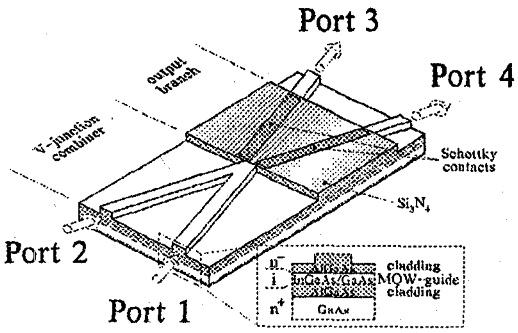

Fig. 6. Schematic view of the optical switch and cross section of the waveguide structure

The operation principle of this device is the generation of the optical waveguide by applying a reverse voltage to the - microstrip - Schottky-electrode and utilizing the quantum confined Stark effect. Contrast ratios of more than -18dB and extinction ratios exceeding 20dB have been obtained experimentally.

High-speed modulation of laser diodes - High-speed waveguide laser diodes are today fabricated as shown in Fig.1 with a cross section given in Fig. 7 [18].

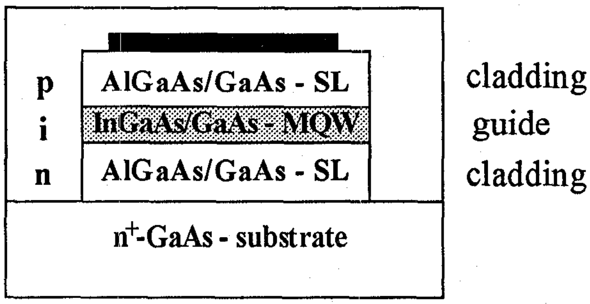

Fig. 7. Cross section of a travelling-wave laser diode..

Again the coplanar metallization structure leads to cut-off frequencies well above 20GHz [19]. In such a laser the center conductor length varies typically between 100µm and about 200µm and due to slow wave effects the metallic contact may exhibit an inhomogeneous voltage distribution. Preliminary results showing the effect of travelling microwave signals have been published recently [20]. It is therefore foreseen, that a layout using microwave propagation effects may lead to further enhancement of the bandwidth of laser diodes. Similar to the vertical modulator structure in Fig. 5 a travelling-wave vertical cavity laser diode can be developed, where different interesting applications are foreseen.

Conclusions - It is shown by various examples that coplanar optoelectronic devices can meet the current requirements for ultra-high-speed operation. In particular, travelling-wave photodetectors, modulators and laser diodes are not limited by the usual RC time constants. Instead, microwave properties determine the bandwidth and the input resistance is given by the characteristic impedance. As a result, travelling wave devices are much more flexible with respect to design parameters and provide a layout ideally suited for further monolithic integration in optical MMICs. Simulation and modelling of the devices can be carried out by using equivalent circuits for the optical and electrical domain, where the interactions can be considered by parametrically controlled elements.

References

[1] D. Jäger, "Slow-wave propagation along variable Schottky contact microstrip line", IEEE Trans. Microwave Theory and Techn., MTT-24, pp. 566-573, 1976

[2] W.C. von Wendorff, M. Welters, and D. Jäger, "Optoelectronic switching in travelling-wave MSM photodetectors using photon energies below bandgap", Electron. Lett. Vol. 26, 1874-1875 (1990)

[3] M. Block and D. Jäger, "Optically controlled travelling wave MSM photodetector for phased array applications", Workshop Proceedings 21st EuMC, Stuttgart 1991, pp. 22-27

[4] D. Jäger, "Travelling-wave optoelectronic devices for microwave and optical applications", Proc. PIERS, MIT Cambridge 1991, p.327

[5] F. Buchali, I. Gyuro, F. Scheffer, W. Prost, M. Block, W. von Wendorff, G. Heymann, F.J. Tegude, P. Speier, and D. Jäger, "Interdigitated electrode and coplanar waveguide InAlAs/InGaAs MSM photodetectors grown by LP MOVPE", Proc. 4th IPRM Conference, Newport, USA, April 1992, pp. 596-599

[6] D. Jäger, "Microwave photonics", ESPRIT/WOIT-conference, Edinburgh 1991, and in "Optical information technology", ed. S.D. Smith and R.F. Neale, Springer-Verlag 1993, pp. 328-333

[7] R. Kremer, G. David, S. Redlich, M. Dragoman, F. Buchali, F.J. Tegude, and D. Jäger, "A high speed MSM-travelling-wave photodetector for InP-based MMICs", Proc. MIOP '93, Sindelfingen, pp. 271-275, 1993

[8] D. Jäger, R. Hülsewede, and R. Kremer, "Travelling-wave MMIC Schottky, MSM and pn diodes for microwave and optoelectronic applications", Proc. CAS '93, Bukarest, pp. 19-29, 1993.

[9] M. Dragoman, M. Block, R. Kremer, F. Buchali, F.J. Tegude, and D. Jäger, "Coplanar InAlAs/InGaAs/InP microwave delay line with optical control", Proc. IEEE LEOS Annual Meeting, Boston, pp. 684-685, 1992

[10] G.A. Vawter, V.M. Hietala, S.H. Kravitz, M.G. Armendariz, "Unlimited-bandwidth distributed optical phase modulators and detectors: design and fabrication issues", Proc. Optical Microwave Interactions, France, 1994, (in press)

[11] K.S. Giboney, M.J.W. Rodwell, J.E. Bowers, "Traveling-wave photodetectors", IEEE Photon. Technol. Lett., Vol. 4, No. 12, pp. 1363-1365, 1992.

[12] D. Jäger, "Characteristics of travelling waves along nonlinear transmission lines for monolithic integrated circuits: A review", Int.J.Electron.Vol.58, 649-669 (1985)

[13] A. Stöhr, O. Humbach, S. Zumkley, G. Wingen, B. Bollig, E.C. Larkins, J.D. Ralston, and D. Jäger, "InGaAs/GaAs Multiple-Quantum-Well modulators and switches", Optical and Quantum Electronics, Vol. 25, pp. S865-S883, 1993.

[14] H. Hayashi and K. Tada, "GaAs Traveling-wave directional coupler optical modulator/switch", Appl. Phys. Lett., Vol. 57, pp. 227-228, 1990.

[15] J.D. Ralston, S. Weisser, I. Esquivias, E. C. Larkins, J. Rosenzweig, P. J. Tasker, and J. Fleissner, "Control of differential gain, nonlinear gain, and damping factor for high-speed application of GaAs-based MQW lasers" IEEE J. Quantum Electron., Vol. 29, No. 6, pp. 1648-59, 1993.

[16] K. Kato, S. Hata, K. Kawano, J. Yoshida, and A. Kozen, "A high-efficiency 50GHz InGaAs multimode waveguide photodetector", IEEE J. of Quantum Electron., Vol. 28, No. 12, pp. 2728-2735, 1992.

[17] A. Stöhr, O. Humbach, R. Hülsewede, A. Wiersch, and D. Jäger, "An InGaAs/GaAs MQW Optical Switch Based on Field-Induced Waveguides ", IEEE Photon. Technol. Lett., Vol. 6, No. 7, pp. 828-830, 1994.

[18] S.D. Offsey, W.J. Schaff, P.J. Tasker, and L.F. Eastman, "Optical and microwave performance of GaAs-AlGaAs and strained layer InGaAs-GaAs AlGaAs graded index separate confinement heterostructure single quantum wel l lasers", IEEE Photon. Technol. Lett., Vol. 2, pp. 9-11, 1990.

[19] S. Weisser, J.D. Ralston, E.C. Larkins, I. Esquivias, P.J. Tasker, J. Fleissner, and J. Rosenzweig, "Efficient high-speed direct modulation in p-doped $In_{0.35}Ga_{0.65}As/GaAs$ multiquantum well lasers", Electron. Lett., Vol. 28, No. 23, pp. 2141-2143, 1992.

[20] D.A. Tauber, R. Spickermann, R. Nagarajan, T. Reynolds, A.L. Holmes, Jr., and J.E. Bowers, "Inherent bandwidth limits in semiconductor lasers due to distributed microwave effects", Appl. Phys. Lett., Vol. 64, No.13, 1994