Optically Controlled Coplanar Transmission Lines for Microwave Signal Processing

Ralf Kremer, Stefan Redlich, Ludger Brings, and Dieter Jäger

Abstract—**This paper reviews optically controlled wave propagation effects in coplanar transmission lines on semiconducting substrate. Special emphasis is laid upon distributed Schottky photodiodes where a depletion layer is formed below the center conductor. The cross section is that of a InAlAs/InGaAs/InP heterostructure, where the thin InGaAs layer is optimized with respect to optical absorption leading to an optical control of phase velocity, time delay or attenuation. Experimentally, phase shifts as high as 110 deg/mm at 9 GHz using an optical power of merely 50 μW are obtained for an MBE grown sample with a suitable doping profile and for backside illumination through the tranparent InP-substrate. The theoretical treatment is based upon an equivalent circuit including the optoelectronic properties under different illumination conditions. It is further shown that periodic structures can sucessfully be used as efficient phase shifters or attenuators with optical control. This leads to interesting applications as optical MMIC's for microwave signal processing.**

I. Introduction

In RECENT years, growing interest has been paid to wave propagation effects in coplanar transmission lines on semiconductor substrate. Besides the use as electrical interconnections in advanced monolithic microwave integrated circuits (MMIC's), special coplanar semiconductor waveguides can be sucessfully employed as traveling-wave devices for several applications and with pronounced advantages as compared to corresponding lumped elements [1]. In particular, the propagation of nonlinear waves in Schottky microstrip and coplanar transmission lines has been studied in detail in the past, see for example [1], with applications to the generation of harmonics [2], [3] or to pulse compression via solitons [4], [5]. Under small signal conditions those structures can be used as variable phase-shifters [6] with bandwidths up to the millimeter wave region [7].

Due to the inherent optoelectronic properties of semiconductor materials, many exciting developments have been seen in the last decade in the realization of optically controlled microwave modulators using various kinds of wave guiding structures and physical mechanisms. The optically generated electron hole plasma can, for example, directly change the dielectric properties of a semiconductor waveguide leading to photoinduced phase shift or attenution [8]. In a coplanar waveguide the free charge carriers lead to a variation of the shunt conductance per unit length giving rise to an optical control of the attenution [9], [10]. The transmission line resembles a distributed photoconductor in this case.

More recently, special attention has been paid to the optical control of Schottky contact coplanar waveguides used as distributed photodiodes mainly under slow wave conditions [11]. Variable phase shifters have been studied in detail where different physical models have been proposed [14]. Bulk GaAs and AlGaAs/GaAs heterostructures where used as the substrate material requiring front side illumination. However, backside optical control could also be demonstrated using a travelling-wave MSM photodetector at photon energies below bandgap [15]. The physical mechanism was traced back to a photoinduced current source to be included in the equivalent circuit of the transmission line [11]. Up to now, the insertion losses of those phase shifters are quite high, an improvement being expected when periodic structures are applied [16], [17].

Optically controlled microwave delay lines for InP based MMIC's were first demonstrated in 1992 [18], [19]. The optical absorption region was a InAlAs/InGaAs Schottky depletion layer on a InP substrate which is transparent for the photon energies used. Hence an improved phase shifter with backside illumination was obtained leading to a true-time delay of 0.55ns/cm in the frequency range of 12 to 22 GHz, and a novel mechanism for an internal optical control was proposed [19].

In this paper, improved InAlAs/InGaAs/InP microwave delay lines with optical control are presented. Giant phase shifts are obtained using a special doping profile in the heterostructures. With backside illumination, two basic physical mechanisms are involved which lead to a change of the internal cut-off frequency and the voltage drop across the depletion layer. The theoretical treatment is based upon a suitable equivalent circuit for the transmission line on layered substrate. Finally, periodic transmission lines with improved parameters are presented.

II. Coplanar InAlAs/InGaAs/InP Microwave Delay Line

In Fig. 1(a) schematic sketch of the Schottky contact coplanar waveguide is shown. The substrate is semiinsulating InP with a bandgap of about 1.35eV. The InGaAs and InAlAs layers are grown by usual MBE, lattice matched to the substrate. The InGaAs film with a bandgap of about 0.75eV serves as the

Manuscript received January 26, 1995; revised April 15, 1995. This work was supported by the Deutsche Forschungsgemeinschaft within the Special Research Center 254 "Very High Frequency and Very High Speed Circuits based on III-V-Compound Semiconductors."

The authors are with FG Optoelektronik, Gerhard-Mercator-Universitat GH Duisburg, D-47048 Duisburg, Germany.

IEEE Log Number 9413682.

0018–9480/95$04.00 © 1995 IEEE

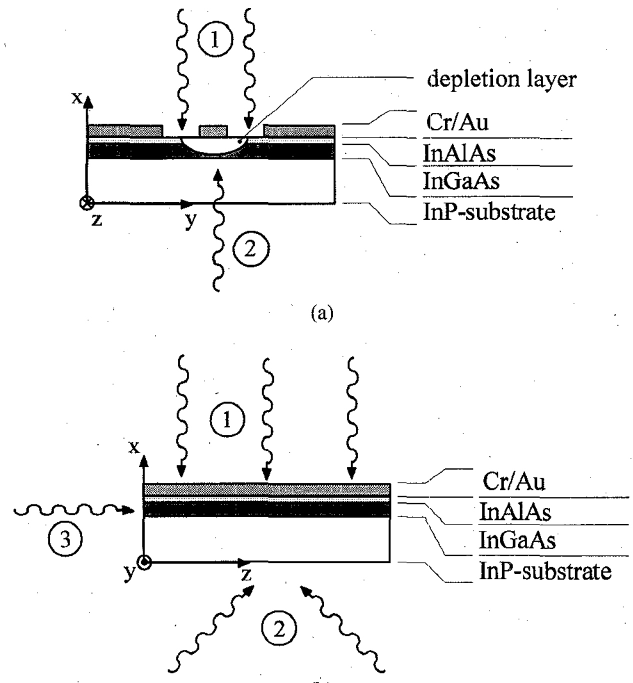


Fig. 1. Schottky contact coplanar microwave delay line. Cross (a) and longitudinal (b) sections with a depletion layer underneath the center conductor. The InGaAs film is the optical absorption layer using different illumination conditions (1)–(3).

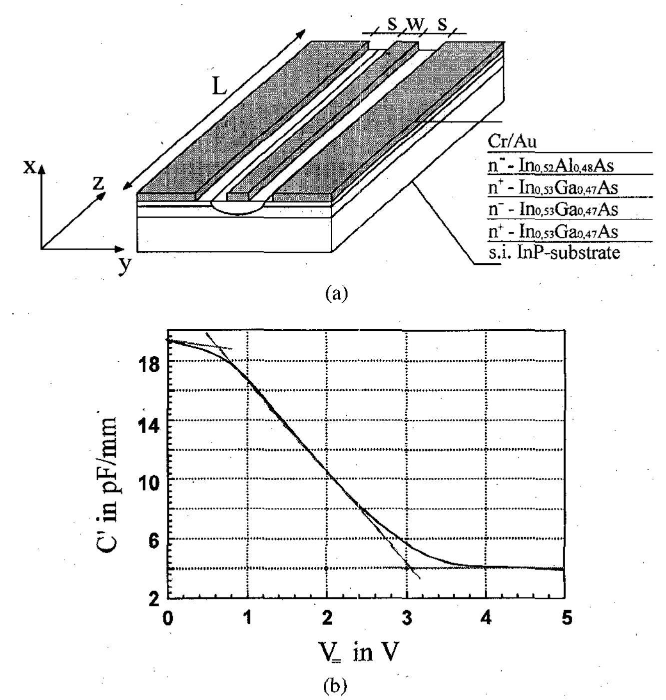


Fig. 2. Experimental transmission line. (a) Doping levels of the different InGaAs layers; from the top to the bottom: $135 * 10^{18}$ cm $^{-3}$; $1.45 * 10^{16}$ cm $^{-3}$; $1.25 * 10^{17}$ cm $^{-3}$; (b) Measured capacitance per unit length versus reverse dc bias voltage for a frequency of 1MHz.

optical absorbing layer. The thin InAlAs film is only used to provide a high Schottky barrier at the metal semiconductor contact using Cr/Au metallisation in the present case. The center contact is reverse biased by an external dc voltage $V_=$ leading to a pronounced depletion layer beneath this conductor. It should be noted at this point that the depletion layer includes the absorbing section and can expand down to the high-resistivity substrate. In Fig. 1(a) and (b) different illumination conditions are shown. Frontside illumination, marked by (1), leads to a situation where parts of the input light beam are reflected from the metallisation pattern because the small gap of width s serves as a mask. The most efficient way of optical input coupling is from the backside (2) when photon energies are used in the region of optical transparency of the InP substrate. Note in this case that a lateral variation of the light spot, in y-direction, shifts the optical absorption region between the depletion layer and the bulk InGaAs. In case of an oblique incidence of two optical beams from the backside (situation (2) in Fig. 1(b)) a moving optical interference pattern is produced and the travelling-wave photodiode generates a millimeter wave signal with a frequency equal to the difference of the optical frequencies [20]. Optical coupling from the edge, configuration (3) in Fig. 1(b), is especially useful when the layer sequence incorporates also an optical waveguide as proposed in [21].

Fig. 2(a) shows the experimental transmission line. Most important is the doping profile of the InGaAs layer which leads to a depletion layer capacitance C which changes drastically when the applied voltage is varied, similar to a hyperabrupt junction [22]. The experimental results in Fig. 2(b) demonstrate a variation of $C' =$ C/L by a factor of > 4 when the bias is changed from 1 V to about 4 V. At 4 V the depletion layer reaches the lower highly doped region which serves as a low series resistance to the capacitance C.

III. Optical Control

The Schottky contact coplanar waveguide can be used as an optically controlled microwave modulator. In Fig. 3 the results of the measured phase coefficient β versus frequency f are plotted. As can be seen the optically induced phase shift is as high as 110 deg/mm at f = 9 GHz, much larger than previously published results (for example 12 deg/mm at 40 GHz from [12], [14] and 9–18 deg/mm within a range of 0.5–8GHz in [13]). When the laser beam is scanned across the lateral y-direction, see Fig. 4, it becomes obvious that the optically sensitive region is that of the depletion layer and that the dc voltage drop $V_=$ is decreased when the laser beam hits the center conductor. Simultaneously, β is increased. The characteristics of the optically controlled microwave modulator can be explained as follows. The transmission line of Fig. 2(a) when illuminated operates as a distributed Schottky photodiode. Accordingly, the optically generated electron hole pairs give rise to two different physical mechanisms: 1) The charge carriers in the depletion layer are separated due to the internal space charge field. As a consequence, a current source is established which drives the depletion region into forward direction similar to what happens in a photovoltaic diode. 2) The charge carriers in the bulk region of the InGaAs film increase the electrical conductivity leading to a smaller series resistance. In summary, the internal physical mechanisms are expected to lead to a change of the depletion layer capacitance via the variation of the dc voltage drop and/or the

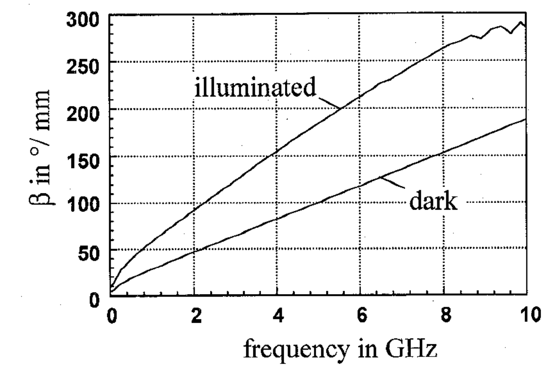


Fig. 3. Measured phase coefficient of the experimental sample of Fig. 2 with $V_0 = 20V, R_0 = 470k = \Omega$ optical power 50 μ W, optical wavelength λ = 1319 nm, Δ z = 10 μm, backside illumination.

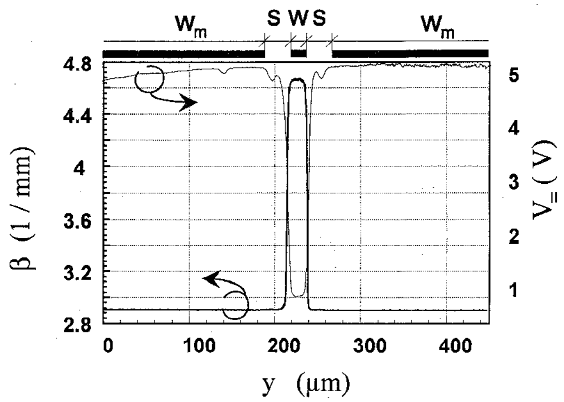


Fig. 4. Variation of β and $V_=$ when the laser beam is scanned in the transversal direction.

semiconductor losses. Hence the time delay and the attenuation are optically controlled and the transmission line operates as an optically controlled microwave phase and/or amplitude modulator. However, because the dielectric properties, i.e., the depletion layer capacitance, determine also the characteristic impedance Z_w, a shift in β changes also Z_w. Additionally, phase and amplitude variation may depend on each other, in general. To study the behavior of the line in more detail, a theoretical analysis is performed in the following.

IV. Numerical Simulation

The following model is based upon an equivalent circuit (Fig. 5) which includes the slow mode region and the quasi-TEM region of the relevant transmission line, [11], [23]. Here L' is the usual inductance per unit length, W_m' and R' account for the metallic and semiconductor (InGaAs) losses due to longitudinal current flow. $G' = I_d'(V_d)/V_d$ results from the exponential Schottky current voltage characteristic, where V_d is the dc voltage drop across the depletion layer. The impressed current source is given by

$$I_{ph}' = (\eta_1 q P_1/W_{ph})\Delta z^{-1} \quad (1)$$

where η_1 is the quantum efficiency, P_1 the optical power absorbed in the depletion region, W_{ph} the photon energy and Δz the length of the illuminated section for backside cw illumination. C_B' and G_B' describe the electrical properties of

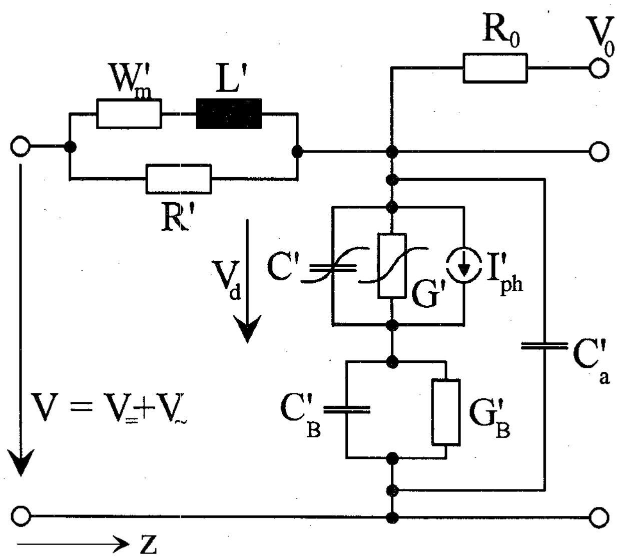


Fig. 5. Equivalent circuit of the Schottky contact coplanar waveguide.

the bulk InGaAs. The photoinduced change of the conductance can approximately be obtained from

$$\Delta G' = (\eta_2 q P_2/W_{ph})_s \frac{\tau}{2}(\mu_n + \mu_p)/\Delta z. \quad (2)$$

Here η_2 is the photoconductor quantum efficiency, P_2 the absorbed power, τ the free carrier lifetime, and μ_n and μ_p the electron and hole mobility, respectively, which may depend on the electrical field. C_a' is the air capacitance per unit length. The external dc voltage V_0 is applied via a load resistor R_0 producing a dc voltage drop $V_=$ across the transmission line. Note that V_0 is applied at a position z_0 which may cause a spatially dependent $V_=(z)$ in case of forward bias condition of the photodiode. $V_\sim$ is the rf voltage.

The photocurrent from (1) controls the depletion layer voltage drop V_d which can be calculated from the equivalent circuit in Fig. 5. This yields

$$\frac{V_0 - V_d - (R_0 + G_B^{-1} I_d(V_d)}{R_0 + G_B^{-1}} = I_{ph'} \quad (3)$$

where $I_{ph} = I_{ph}'\Delta z$ is the total current, and $G_B = G_B' L$. $I_d(V_d)$ is the usual current voltage characteristic of the Schottky diode with length L. In a first order parallel-plate approximation the depletion layer capacitance for a hyperabrupt junction can be calculated from

$$C' = C^*(V_D + V_d)^{-m} \quad (4)$$

where V_D is the Schottky contact diffusion potential and m is determined by the doping profile [22]; m is also a measure for the varactor sensitivity according to

$$m = -\frac{dC'V_d}{C'dV_d}. \quad (5)$$

Equations (1) to (4) can be used to determine the characteristic impedance Z_w of the transmission line and the propagation constant $\gamma = \alpha + j\beta$.

The transmission line parameters for the circuit in Fig. 5 have been determined numerically using typical data for a Schottky contact coplanar line of Fig. 2(a). In order to

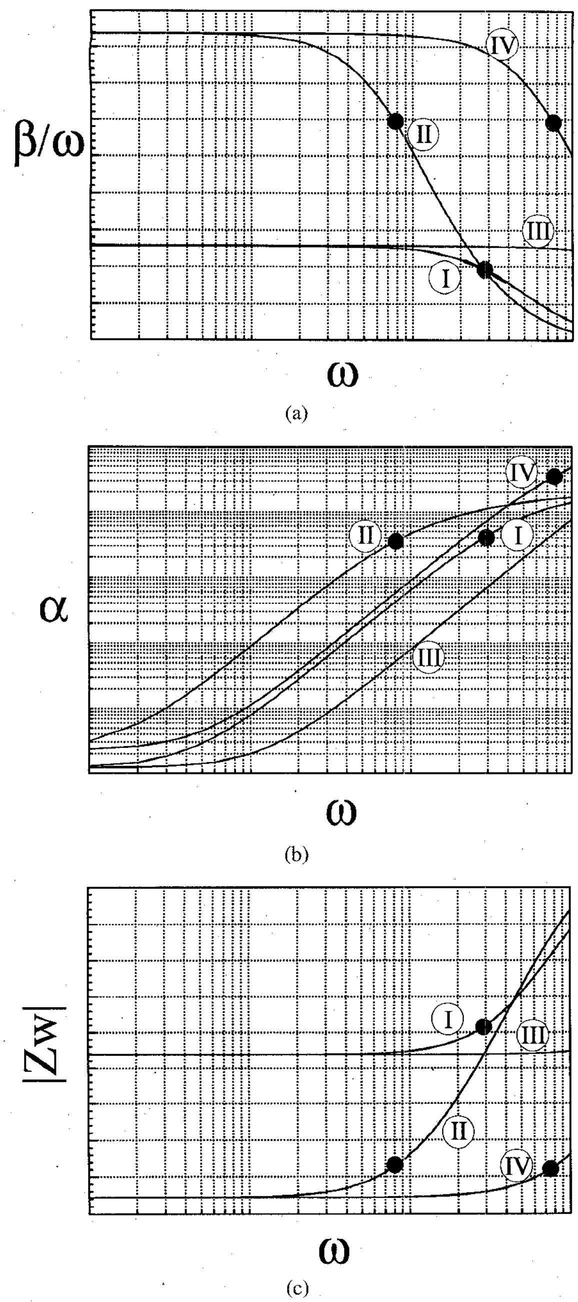


Fig. 6. Delay time per unit length (a), attenuation (b) and magnitude of the characteristic impedance (c) versus frequency. Curves I denote the unilluminated case, curve II result from the photocurrent changing C', and and curves I and II are changed to curves III and IV, respectively, when G'_B is increased optically. The • marks the transition between the slow mode (lower frequencies) and the quasi-TEM (higher frequencies) regions.

demonstrate the underlying principle of an optically controlled phase shifter and attenuator by using the same semiconductor heterostructure and geometrical data, the following results are plotted using arbitrary units.

For that purpose, in Fig. 6 the delay time per unit length, the attenuation and the magnitude of the characteristic impedance are despicted as a function of the microwave frequency in the slow mode and the transition region to quasi-TEM wave propagation [23].

From Fig. 6 it is concluded, that a large photoinduced phase shift can be achieved in the slow mode region with the additional advantage of a dispersionless time delay. The losses remain small in this region of lower frequencies. The phase shift is obtained by illumination of the depletion layer. However, Fig. 6(c) points out, that $|Z_w|$ is also changed dramatically. Thus an optimized device keeps the optically induced phase shift per unit section small while enhancing the length L to obtain the desired phase control: The optimization has to consider the increase of the insertion loss due to the overall attenuation and a decrease due to a lower mismatch. In this slow mode region an optically controlled attenuator can be realized with constant β and $|Z_w|$, compare curves II and IV or I and III.

At higher frequencies dispersion occurs due to the $G'_B C'$ relaxation frequency. Here frequencies can be found, where for example $|Z_w|$ remains constants and β is slightly shifted, see curves II and III. However, the losses are much higher which yields large insertion losses. As a common conclusion from Fig. 6, the most interesting region is the slow mode region where the only drawback is caused by the optical variation of $|Z_w|$.

The following discussion opens a way to overcome this problem.

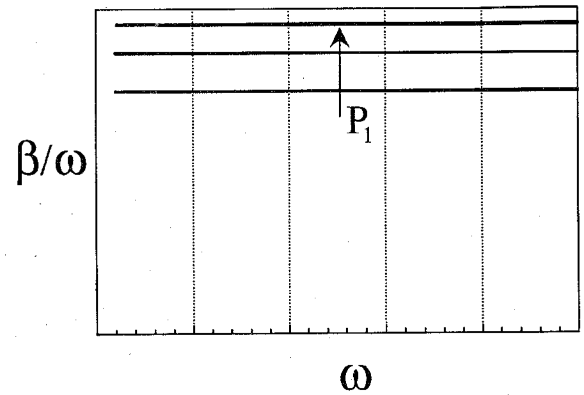
V. Periodic Transmission Line

The basic idea of optically controlled periodic transmission lines is as follows. The model starts with a usual homogeneous transmission line of high characteristic impedance which is periodically loaded with Schottky varactor diodes [1]. In the slow mode region of this structure, the phase is shifted again via a control of the capacitance of the diode. However, because a decrease, for example, of the capacitance enhances the low frequency characteristic impedance, but increases also the cut-off frequency of the Bragg structure, there is a frequency range where the phase is shifted while the characteristic impedance is constant. Note that a Π-structure is necessary in this case (for a sketch of the structure see Fig. 8).

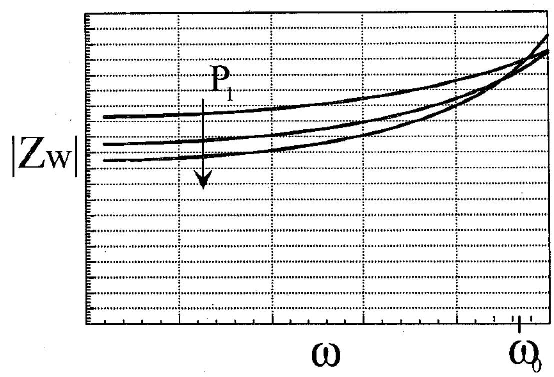
The numerical analysis is carried out for a structure where the diodes are characterized by an equivalent-lumped-circuit as given by the shunt admittance in Fig. 5. The diodes are connected by an R-L circuit to describe the transmission line (for further details see [1]). Fig. 7 shows numerical results for the time delay per section, β/ω, and for $|Z_w|$. As can be seen, for increasing optical input power into the depletion region of the diode, β/ω is enhanced while $|Z_w|$ remains almost constant in the vinicity of ω/ω_0. Note also that the dispersion is still negligible. It should further be mentioned that the phase change can be enhanced due to resonance effects in the periodic structure.

VI. Microwave Signal Processor

An optically controlled microwave signal processor has been developed. A basic building block is shown in Fig. 8. The input microwave signal is divided into two channels via a microwave power splitter. Each channel consists of a phase shifter (periodic transmission line) and an attenuator, both optically controlled. The output signals can be combined finally. This block is studied as a demonstrator for applications



(a)



(b)

Fig. 7. Microwave propagation along a periodic Schottky transmission line under optical control; (a) time delay per unit length and (b) magnitude of the characteristic impedance versus frequency. Parameter is the optical power.

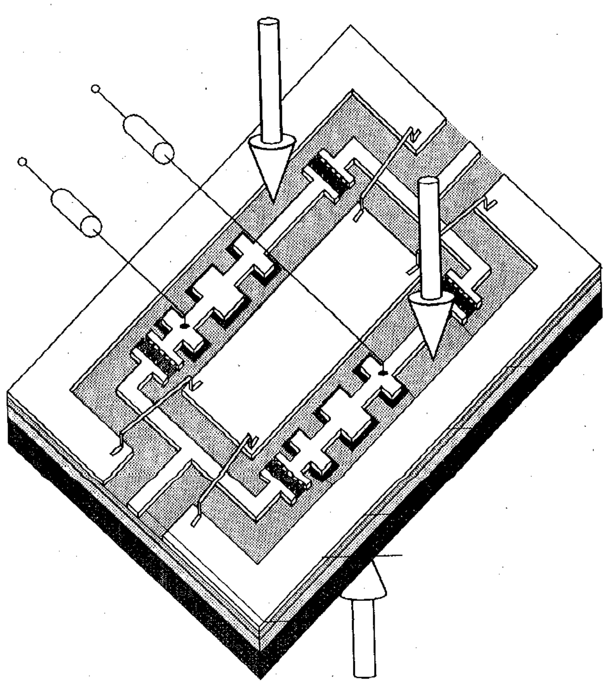


Fig. 8. Basic building block of an optically controlled microwave signal processor.

in phased array systems, transversal filtering, time lenses, signal processing, etc., where, however, a number of additional channels have to be employed. Note that the structure of Fig. 8 is suitable for optical MMIC technology.

VII. Conclusion

Improved optically controlled microwave phase shifters and attenuators have been presented in this paper. The following important advantages are obtained: A heterostructure on InP-substrate suitable for efficient backside optical coupling providing two physical mechanisms described by a photocurrent and a photoconductor; high optical sensitivity as a result of a suitable doping profile and of resonance effects in a periodic structure; true time delay and attenuation control without changing the other transmission line parameters; structure suitable for integration of both devices; an equivalent circuit for theoretical analysis. Finally, the outline of a basic building block of an optically controlled microwave signal processor is sketched.

References

[1] D. Jäger, "Characteristics of travelling waves along nonlinear transmission lines for monolithic integrated circuits: A review," *Int. J. Electron.*, vol. 58, pp. 649–669, 1985.

[2] B. Wedding and D. Jger, "Phase-matched second harmonic generation and parametric mixing on nonlinear transmission lines," *Electron. Lett.*, vol 17, pp. 76–77, 1981.

[3] D. Jäger, "Nonlinear slow-wave propagation on periodic Schottky coplanar lines," in *IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.*, St. Louis, 1985, pp. 15–17.

[4] M. Dragoman, R. Kremer, and D. Jäger, "Pulse generation and compression on a travelling-wave MMIC Schottky diode array," in *Ultra-Wideband, Short-Pulse Electromagnetics,* H. L. Bertoni, L. Carin, and L. B. Felsen, Eds. New York: Plenum, 1993, pp. 67–74.

[5] D. Jäger, "Pulse generation and compression on nonlinear transmission lines, workshop on picosecond and femtosecond electromagnetic pulses: Analysis and applications," in *MTT-S Symp. Dig.,* Atlanta, 1993, pp. 37–57.

[6] D. Jäger and W. Rabus, "Bias-dependent phase delay of Schottky contact microstrip line," *Electron. Lett.*, vol. 9, pp. 201–203, 1973.

[7] V. M. Hietala, Y. R. Kwon, and K. S. Champlin, "Broadband continiously variable microwave phase shifter employing a distributed Schottky contact on silicon," *Electron. Lett.*, vol. 23, pp. 675–677, 1987.

[8] M. Tsutsumi and A. Alphones, "Optical control of millimeter waves in the semiconductor waveguide," *IEICE Trans. Electron.*, vol. E76-C, pp. 175–182, 1993.

[9] W. Platte, "Photoinduced microwave attenuation in LED-controlled semiconductors coplanar waveguides," *AE*, vol. 42, pp. 322–325, 1988.

[10] S. E. Saddow, B. J. Thedrez, and C. H. Lee, "An optoelectronic attenuator for the control of microwave circuits," *IEEE Microwave and Guided Wave Lett.*, vol. 3, pp. 361–362, 1993.

[11] D. Jäger, M. Block, D. Kaiser, M. Welters, and W. von Wendorff, "Wave propagation phenomena and microwave-optical interaction in coplanar lines on semiconductor substrate," *J. Electrom. Waves and Appl.*, vol. 5, pp. 337–351, 1991.

[12] P. Cheung, P. D. Neikirk, and T. Itoh, "Schottky-biased, optically controlled coplanar waveguide phase-shifter," *Electron. Lett.*, vol. 25, pp. 1301–1302, 1989.

[13] D. Kaiser, M. Block, and D. Jäger, "Optically controlled phase shift of Schottky coplanar lines," *Electron. Lett.*, vol. 25, pp. 1575-1576, 1989.

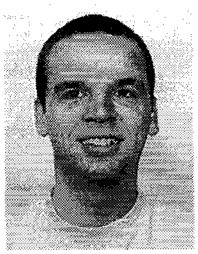
[14] P. Cheung, D. P. Neikirk, and T. Itoh, "Optically controlled coplanar phase shifter," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 586–595, 1990.

[15] 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, pp. 1874–1875, 1990.

[16] Y. D. Lin, D. P. Neikirk, and T. Itoh, "Coplanar waveguide phase shifter controlled by a spatially periodic optical illumination," *Int. J. Infrared and Millimeter Waves*, vol. 8, pp. 1027–1036, 1987.

[17] D. Kaiser, M. Block, and D. Jäger, "Variable phase shift of spatially periodic proton-bombarded Schottky coplanar lines," *Electron. Lett.*, vol. 25, pp. 1135–1136, 1989.

[18] M. Dragoman, M. Block, R. Kremer, F. Buchali, F. J. Tegude, and D. Jäger, "Coplanar microwave phase shifter for InP-based MMICs," in *Proc. ESSDERC'92*, Leuven, pp. 421–424.
[19] M. Dragoman, M. Block, R. Kremer, F. Buchali, F. J. Tegude, and D. Jäger, "Coplanar InAlAs/InGaAs/InP microwave delay line with optical control," in *Proc. IEEE LEOS Annual Meet.*, Boston, 1992, pp. 684–685.
[20] J. Soohoo, S.-K. Yao, J. E. Miller, R. R. Shurtz II, Y. Tanr, and R. A. Gudmundsen, "A laser-induced travelling-wave device for generating millimeter waver," *IEEE Trans. Microwave Theory Tech.*, vol MTT-29, pp. 1174–1181, Nov. 1981.
[21] D. Jäger and R. Kremer, "Travelling-wave optoelectronic devices for microwave applications," in *Proc. Int. 1994 IEEE MTT-S Top. Meet. Optical Microwave Interactions*, Abbaye des Vaux de Cernay, France, Nov. 1994, pp. 11–14.
[22] S.M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981, pp. 114–115.
[23] D. Jäger, "Slow-wave propagation along variable Schottky contact microstrip line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 566–573, 1976.



Ralf Kremer was born December 25, 1964. He received the degree in electrical engineering at the Universitat-GH-Duisburg in 1984, and the Dipl.-Ing. degree in electrical engineering at the Universitat-GH-Duisburg in 1991. He is currently a Research Associate at the University of Duisburg working toward the Ph.D. degree.

He has published 13 papers in the field of microwave optoelectronics and nonlinear transmission lines. Experience: III-V monolithic optoelectronic microwave integrated circuits, design and measurement of travelling wave photodetectors and optically controlled microwave circuits.

Stefan Redlich studied electrical engineering at the Universitt-GH-Duisburg from 1987 to 1993. He received the Dipl.-Ing. degree in electrical engineering at the University-GH-Duisburg in 1993. He is currently a Research Associate at the University of Duisburg, working toward the Ph.D. degree.

He held an apprenticeship in communication electronics at Philips Ltd. in Krefeld from 1982 to 1986. He has published 10 papers in the field of electro-optic measurement techniques, microwave optoelectronics and molecular beam epitaxy

Mr. Redlich was awarded the "EuMC Microwave Prize" at the 23rd European Microwave Conference in Madrid, Spain.

Ludger Brings was born March 26, 1967 in Wesel (Germany). He has studied electrical engineering at the Gerhard-Mercator-Universitat-GH-Duisburg since 1989.

He held an apprenticeship in energy electronics at AUMUND Ltd. in Rheinberg from 1983 to 1987.

Dieter Jäger was born in Tratten/Ranten, Austria. He received the Diplomphysiker, Dr. rer.nat., and habilitation degrees in physics, all from the Westfäische Wilhelms-Universitt, Münster, F.R. Germany, in 1969, 1974, and 1980, respectively.

From 1974 to 1990 he was Leader of a research group at the Institute for Applied Physics, University of Münster, where he became an Associate Professor of Physics in 1985. In 1989 he was Visiting Professor at the University of Duisburg. In 1990 he joined the Faculty of Electrical Engineering of the University of Duisburg where he is head of the Department of Optoelectronics. He is currently engaged in nonlinear phenomena in solid-state devices where he is concerned with nonlinear microwaves for MMIC applications as well as nonlinear optics, ultrafast electrooptics, and optical bistability in semiconductors for optoelectronic signal processing. His research interests include ultrafast optoelectronics for microwave modulation and power generation and picosecond electrooptical measuring techniques. He has also activities in the areas of optical neural technology and optoelectronics for medical applications.

Dr. Jäger is a member of the German Physical Society (DPG), the German Vacuum Association (DVG), the German Society of Information Technology (VDE, ITG), and the German Association for Applied Optics (DGaO).