Modelling of Integrated Acoustooptical Devices

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Introduction

During the last decades a large variety of integrated acoustooptical devices like rf spectrum analysers, intensity modulators, frequency converters, beam deflectors, optical wavelength filters, space switches, etc. have been in the interest of international research activities. The principle of operation of all these components is based on the interaction of optical modes guided in dielectric waveguides with surface acoustic waves (SAW). Traditionally, ferroelectric lithium niobate is used as substrate material due to its excellent electrooptic, elastooptic, and piezoelectric properties. The development and optimisation of such components require a profound understanding of the acoustooptical interaction process. This includes – in addition to the experimental and technological know-how – a suitable theoretical description and numerical modelling.

In this contribution we present the analysis of a sophisticated integrated acoustooptical polarisation converter as it is used as key component of recent high performance integrated acoustooptical wavelength filters and multiplexers in lithium niobate [1,2,3].

Integrated Acoustooptical Polarisation Converter

Fig. 1 shows the design of such a converter. Using titanium indiffusion technology an acoustical waveguide structure is fabricated. The material is stiffened by the dopant and hence the velocity of sound is increased in the cladding regions resulting in a lateral confinement of the SAW. The SAW itself is excited by transducer electrodes and propagates along the structure as indicated by the arrow. Light is guided in a single mode dielectric waveguide also fabricated by titanium indiffusion. The interaction with the SAW leads to a TE/TM polarisation conversion if the phase matching condition is satisfied, i. e. the difference between the propagation constants of the TE and TM polarised optical modes has to be matched by the SAW propagation constant. This immediately leads to a wavelength selectivity which can be tuned by adjusting the SAW frequency. The interaction region is terminated by a pair of SAW absorbers. Using an acoustic directional coupler geometry the interaction strength is apodised yielding a strong suppression of sidelobes in the conversion characteristics [4]. Placing such a converter between, e. g., orthogonal polarisers a tuneable wavelength filter can be realised.

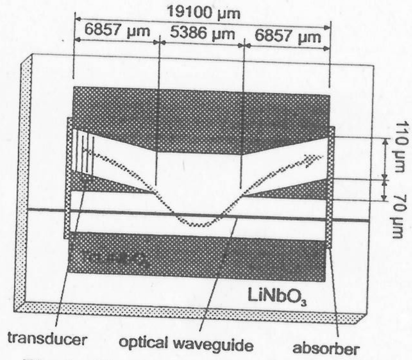

Fig. 1: Structure of integrated acoustooptical polarisation converter

Surface Acoustic Waves

In a piezoelectric crystal surface acoustic waves can be described by a vector field of four components. They represent the mechanical elongations of each crystal element along the three spatial axes from its respective equilibrium position and an electric scalar potential. Both amplitude and relative phase relations have to be considered. The wave equations can be derived from Newton's equation of motion and the Gaussian law – they form a set of coupled second order partial differential equations. For planar geometries with homogeneous layers solutions of these wave equations can be found quite easily. For *X*-cut lithium niobate with *Y*-propagation one finds that one SAW field component – the elongation along the *X*-axis – is dominant [5].

This motivates a scalar model for the SAW propagation in waveguide structures. Similar to the effective-index-method for optical strip waveguides [6] a scalar wave equation is assumed. The one-dimensional "effective index" profile is taken from measured SAW velocities in pure and titanium indiffused lithium niobate. This approach allows to model the propagation of SAWs in simple waveguides and also in more complicated waveguide structures like acoustical directional couplers. The advantage of this method is its simplicity. The requirements in numerical power are quite low which makes it suitable for a routine modelling tool. Furthermore, the predictions agree reasonably well with experimental results [4].

Nevertheless, it is important to establish an analysis of guided SAWs which is based on the full vectorial wave equations, e. g., to examine the validity of the scalar model. This can be achieved using the finite element method (FEM). This approach is based on finding stationary points of a Lagrangian functional which comprises only first order derivatives of the field components being a very important property with respect to the numerical stability of the algorithm. A domain discretisation of the acoustic waveguide cross section leads to a generalised eigenvalue problem of the form $A\,x = \lambda\,B\,x$. The stiffness matrix A contains the local elastic, piezoelectric and dielectric properties of the crystal, the mass matrix B the local mass densities. Thus, the functional allows to explicitly reflect the local variation of the material parameters due to the titanium indiffusion. However, it should not be concealed that until now only few experimental data are available for this. Therefore, we are forced to make some reasonable assumptions. For a given SAW wavelength the eigenvalue λ represents the SAW frequency and the eigenvector x the SAW mode distribution. The algorithm to solve the generalised eigenvalue problem is based on the minimisation of a Rayleigh quotient using a conjugate gradient method [7]. The important feature of this algorithm is that it preserves the band structure of the above matrices. This makes it feasible to run the analysis on common PC type machines offering the potential for routine use.

Acoustooptical Interaction

The mechanical strains and the electric field produced by the SAW induce a modulation of the crystal's index ellipsoid due to the elastooptic and electrooptic effect, respectively. According to coupled mode theory this perturbation can lead to an efficient power transfer between different optical modes if phase matching is satis-

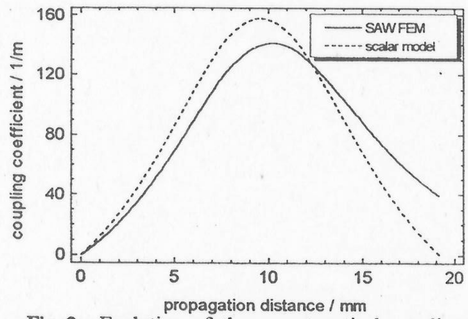

Fig. 2: Evolution of the acoustooptical coupling coefficient along the converter.

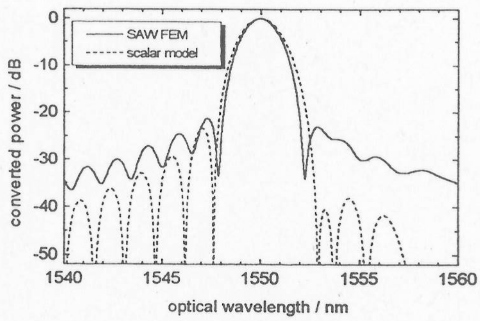

Fig. 3: Computed conversion characteristics.

fied. The interaction efficiency is determined by the spatial overlap of the participating optical modes and the acoustically induced dielectric perturbation. With the help of the FEM based SAW analysis it is now – for the first time – possible to rigorously compute the cross sectional profile of this disturbance and subsequently the resulting coupling factor. The scalar model is not capable of this. It only allows us to assume the coupling factor being proportional to the scalar SAW amplitude at the location of the optical waveguide. Fig. 2 shows the coupling factor evolution as computed by the two different models within the converter structure currently used for our integrated acoustooptic devices. One observes that the FEM predicts a slightly different optimum interaction length. Using the coupled mode equations the conversion characteristics are readily computed. Results are shown in Fig. 3. Significant differences between the two approaches can only be identified beyond the –20 dB level. As the device performance has nowadays improved to reach these levels the increased computational effort for the FEM analysis is justified.

Conclusion

The solution of the vectorial wave equations for SAW propagating in acoustical waveguide structures using the FEM allows a rigorous analysis of the acoustooptical interaction process in integrated acoustooptical mode converters. In combination with the established scalar approximation this opens the door for a new quality of design and modelling tools.

References

[1] H. Herrmann, K. Schäfer, C. Schmidt "Low-Loss Tunable Integrated Acoustooptical Wavelength Filter in $LiNbO_3$ with Strong Sidelobe Suppression," IEEE Photon. Technol. Lett. 10 (1), 120-122 (1998)

[2] F. Wehrmann, Ch. Harizi, H. Herrmann, U. Rust, W. Sohler, S. Westenhöfer, "Integrated Optical, Wavelength Selective, Acoustically Tunable 2 × 2 Switches (Add-Drop Multiplexers) in $LiNbO_3$," IEEE J. Select. Topics Quantum Electron. 2 (2), 263-269 (1996)

[3] D. A. Smith, R. S. Chakravarthy, Z. Bao, J. E. Baran, J. L. Jackel, A. d'Allesandro, D. J. Fritz, S. H. Huang, X. Y. Zhou, S.-M. Hwang, Al. E. Willner, K. D. Li, "Evolution of the Acousto-Optic Wavelength Routing Switch," J. Lightwave Technol. 14(6), 1005-1019 (1996)

[4] H. Herrmann, U. Rust, K. Schäfer, "Tapered Acoustical Directional Couplers for Integrated Acousto-Optical Mode Converters with Weighted Coupling," J. Lightwave Technol. 13 (3), 364-374 (1995)

[5] A. J. Slobodnik, Jr., E. D. Conway, R. T. Delmonico, "Surface Acoustic Wave Velocities," in Microwave Acoustics Handbook, vol. 1 A, Air Force Cambridge Research Labs, AFRCRL-TR-73-0597 (1973)

[6] G. B. Hocker and W. K. Burns, "Mode Dispersion in Diffused Channel Waveguides by the Effective Index Method," Appl. Opt. 16, 113-118 (1977)

[7] H. Yang, "Conjugate Gradient Methods for the Rayleigh Quotient Minimization of Generalized Eigenvalue Problems," Computing 51, 79-94 (1993)