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Optics and Lasers in Engineering 45 (2007) 458–462
OPTICS and LASERS in ENGINEERING

Digital optical switch based on amorphous silicon waveguide

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Available online 24 July 2006

Abstract

In this paper, the performance of a digital optical switch, operating at the infrared communications wavelength of 1550 nm and based on the thermo-optic effect in amorphous silicon, are investigated. We prove that the strong thermo-optic effect of amorphous silicon, combined with the possibility of realising micrometric integrated structures, allow the design of promising integrated switches. The device, designed for low-cost photonic applications, could be easily integrated in silicon optoelectronic circuits.

Keywords: Integrated optics devices; Optoelectronics

1. Introduction

Nowadays, a multitude of photonic switching technologies are candidate for all-optical network, i.e. two- (2D) and three-dimensional micro-electro-mechanical systems (MEMS), electro-optics, thermo-optics, liquid crystals and acousto-optic; probably, in the future, a typical telecommunications system could make use of several levels of switching technology [1,2].

Waveguide switches are based on a controlled refractive index and/or absorption variation in order to influence the light propagation. The advantage of the waveguide structure could be the economy of scale. The integration of many devices on a single substrate should reduce the cost per function and increase the stability and the robustness of the optical circuit. The reliability of the waveguide-based switches is potentially high because there are no moving parts. From reliability considerations, the thermo-optic effect (TOE) is principally suited as their operational principle, due to its polarisation independent nature. Moreover the speed of TOE-based waveguide components is adequate for all routing applications.

In order to design an integrated optical device, the most important aspect to study is the determination of the optical modes that can propagate in a given waveguide characterised by an uniform cross-section: the so-called *mode-solving techniques* address this question. The task of a mode solver, for a specified value of operating wavelength, is to determine the values of propagation constant and modal pattern for each desired mode. The techniques for obtaining the propagation constant for a particular waveguide structure vary and can be divided into several method categories. A possible approach utilises numerical methods.

All mode solvers assume that the waveguide section is unaltered along the propagation direction. Most photonic devices involve propagation in structures that are non-uniform, and techniques for handling this include beam propagation method (BPM). The BPM is essentially a particular approach for approximating the exact wave equation for monochromatic wave and solving the resulting equations numerically. Originally introduced to waveguide optics by Feit and Fleck [3] in late 70s, the BPM was initially based on FFT algorithm. More recent BPM studies, however, show that finite-difference-based BPM (FD-BPM) numerical schemes demonstrate a performance superior to the conventional FFT BPM [4].

Digital optical switch (DOS) has become, since its invention, a very attractive component for space switching in multi-wavelength optical communication system applications. For reliable operation, most of the other types of optical switches, which rely on effects such as interference, reflection or absorption, need sophisticated feed-back

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0143-8166/$ - see front matter
doi:10.1016/j.optlaseng.2006.04.009

loops and tight wavelength or temperature control. On the contrary, its step-like switch response makes the DOS highly insensitive to wavelength, polarisation, and other physical parameters that may affect switching [5–8]. A variety of switch arrays consisting of DOSs have already realised using LiNbO3 [9–11], III–V semiconductor [12], polymers [13], silicon resin [14] and silica on silicon [15].

In recent years, hydrogenated amorphous silicon (a-Si:H), grown by plasma-enhanced chemical vapour deposition (PECVD), has gained considerable attention due to its unique characteristics of transparency at the infrared wavelengths, the refractive index tunability and technological compatibility with all microelectronic processes. As a consequence, several a-Si:H-based optoelectronic devices, such as light-emitting diodes [16], photodetectors [17] and optical modulators [18] have been successfully fabricated.

In this paper, taking into account the amorphous silicon properties combination, i.e. a high TOE coefficient and a low thermal conductivity, the performance of a DOS, based on amorphous silicon waveguides, are analysed. The device could find application in low-cost fibre optic systems.

2. Design of device

In order to design semiconductor rib waveguides for optical communications, care should be taken to ensure single-mode propagation for their coupling with single-mode fibres. It is possible to suppose that the single-mode condition for rib waveguide has to be similar to the single-mode condition for slab waveguides of the same dimensions, but, in practical, the correlation is not direct. Consequently, a criterion has to be determined for the right design of the waveguide transverse section, in order to ensure the single-mode propagation [19].

It is worth noting that the rib waveguide may be multimode in the vertical direction but due to well-defined proportional sizes of the height and the width in the central section, it can support only one bound mode (for each polarisation). In fact, all high-order modes in the central rib region having propagation constant lower than that of the fundamental mode of the slab waveguide in the side region are filtered out by leaking away. Only the fundamental mode in the central rib region survives since only its propagation constant is higher than that of the fundamental mode of the slab waveguide in the side region (see Fig. 1). It should be noted that this condition is equivalent to the following statement: the effective refractive index of the mode with the mode number $m = 1$ in the central region should be lower than the effective refractive index of the fundamental mode in the side region (II). It is possible to demonstrate that the single-mode propagation condition for large cross-section waveguides its simultaneous fulfilment of following relationship:

$$t < \frac{r}{(1-r^2)^{1/2}}, \quad r > 0.5, \quad t = \frac{w}{H}, \quad r = \frac{h}{H}.$$

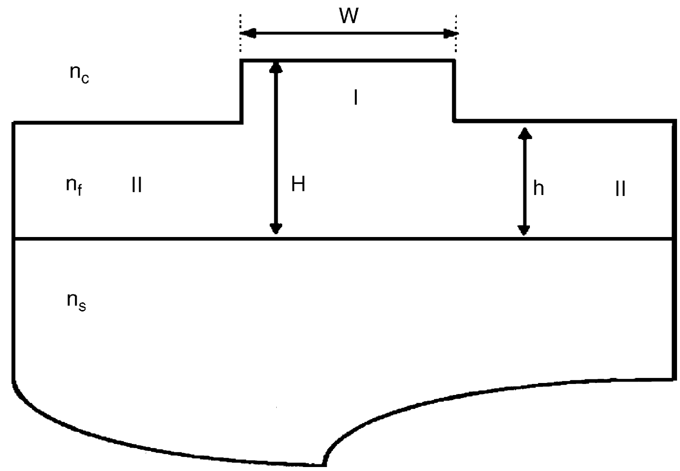

Fig. 1. Schematic of rib waveguide; the central and the side region are designated as I and II, respectively.

In order to determine the 2D profile of a layer structure, we have chosen the finite difference (FD) mode solver [20,21]. This method is applicable to arbitrarily shaped optical waveguide. In FD method, partial differential equations are discretised and then transformed to matrix equation. The calculations of propagation constants and optical field distributions are then equivalent to obtaining eigenvalues and eigenfunctions of the coefficient matrices. Early mode solvers were based on the scalar wave equations which is a simple self-adjoin problem with a symmetrical coefficient matrix, the eigenvalues of which are easy to find. However, the scalar approximation does not discriminate between transverse electric (TE) and transverse magnetic (TM) modes and is only accurate when the refractive index difference is so small that the system is effectively degenerate. Consequently, polarised formulations were needed for improved modelling. The semivectorial finite difference (SVFD) method proved to be very effective. The computation of the propagation constants using this method requires the solution of an asymmetric eigenvalue problem rather than a symmetric one. New sparse asymmetric eigenvalue solvers have been developed to overcome this difficulty and now SFVD is one of the most commonly used techniques for analysis of integrated optical waveguides. Even though these semivectorial methods are very effective, they do not provide a full vectorial description of the guiding process. The standard solution of the vectorial wave equation by means of finite differences leads to a large asymmetric eigenvalue problem [21]. However given that the hybrid nature of the modes is usually only a second order effect, we have developed only semivectorial calculations.

One of the key issues in implementing a numerical scheme, such as the FD method, to solve a partial differential equation, such as the Helmholtz equation, is the numerical boundary conditions. Several techniques have been used in the FD method to absorb the outgoing waves. An important technique is the transparent boundary condition (TBC). Radiation is allowed to freely escape