INTEGRATED OPTICS: TECHNOLOGY, DEVICES AND APPLICATIONS*

P. RICHTER

Department of Atomic Physics
Technical University H-1521, Budapest

Received July 1, 1989

Abstract

Signal transmission and processing can be carried out with numerous advantageous features by optical methods. Practical application call for miniaturized integrated devices. Recent technologies and applications are reviewed.

1. Introduction

The transmission and processing of signals carried by optical beams rather than by electrical currents or radio waves has been a topic of great interest ever since the early 1960's, when the development of the laser first provided a stable source of coherent light for such applications. Laser beams can be transmitted through the air, but atmospheric variations cause undesirable changes in the optical characteristics of the path from day to day, and even from instant to instant. Laser beams also can be manipulated for signal processing, but that requires optical components such as prism, lenses, mirrors, electrooptic modulators and detectors. In the late 1960's, the concept of "integrated optics" emerged, in which wires and radio links are replaced by light-waveguiding optical fibers rather than by through-the-air optical paths, and conventional electrical integrated circuits are replaced by miniaturized optical integrated circuits (OIC's).

For many years, the standard means of interconnecting electrical subsystems, including integrated circuits, has been either the metallic wire or the radio link through the air. The *optical fiber waveguide* has many advantages over either of these conventional methods. The most important of these are:

Advantages

Immunity from electromagnetic interference (EMI)
Freedom from electrical short circuits or ground loops
Safety in combustible environment
Security from monitoring

---

* Dedicated to Prof. J. Giber on the occasion of his 60th birthday.

Low-loss transmission
Large bandwidth (i.e., multiplexing capability)
Small size, light weight
Inexpensive, composed of plentiful materials

Major disadvantage

Cannot be used for electrical power transmission

Optical integrated circuits have been developed to replace electrical integrated circuits or conventional optical signal processing systems composed of relatively large discrete elements. The major advantages of the OIC are:

Advantages

Increased bandwidth
Expanded frequency (wavelength) division multiplexing
Low-loss couplers, including bus access types
Expanded multipole switching (number of poles, switching speed)
Smaller size, weight, lower power consumption
Batch fabrication economy
Improved reliability
Improved optical alignment, immunity to vibration

Major disadvantage

High cost of developing new fabrication technology

2. Materials and technologies for integrated optics

There are two basic forms of optical integrated circuits. One of these is the hybrid, in which two or more substrate materials are somehow bonded together to optimize performance for different devices. The other is the monolithic OIC, in which a single substrate material is used for all devices:

Substrate materials for optical integrated circuits are

Passive (incapable of light generation)
    glass
    quartz
    lithium niobate

  - lithium tantalate
  - tantalum pentoxide
  - niobium pentoxide
  - silicon
- *Active* (capable of light generation)
  - gallium arsenide
  - gallium aluminium arsenide
  - gallium arsenide phosphide
  - gallium indium arsenide
  - other III—V and II—VI direct bandgap semiconductors

The technologies applied depend on the substrate material. Some examples are given in the following:

2.1. Glass

The optical waveguide fabrication in glass is generally accomplished by an ion exchange (*I/E*) process. Typically, sodium (Na^+) or potassium (K^+) ions of the glass are exchanged by ions like Ag^+, Tl^+, Li^+ etc. which are solved in melts at temperatures between 200°C and 400°C. The achieved refractive index increase which is essential for the light guiding properties, is in the order of 10^{-2} to 10^{-1}.

The *I/E* process itself may be either thermal, leading to characteristic diffusion profiles, or electrical field assisted, yielding deep step index profiles. Details of the *I/E* theory and technology are reviewed in [1, 2].

2.2. Silicon

Silicon as substrate material for integrated optical devices has been considered for years, however, with increasing emphasis in the recent time. Silicon is specially attractive, because it offers the potential for the integration of optical, optoelectronic and electronic components on one substrate. Furthermore, the silicon material and technology is the best known so that

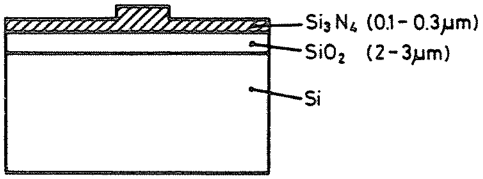

Fig. 1. Schematic configuration of a stripe (ridge) waveguide on silicon

reliable and high quality devices for signal processing and sensor applications may be expected at low cost.

Besides sputtering and thermal oxidation, the chemical vapor deposition (CVD) is most commonly used to fabricate high quality, low loss waveguiding films on thermally grown SiO_2-layers [3].

Figure 1 shows schematically the structure of a Si_3N_4-stripe waveguide. The 2—3 μm thick thermally grown SiO_2 layer serves as optical isolation from the Si-substrate.

The light guiding Si_3N_4 layer of 0.1—0.3 μm thickness may be fabricated by low pressure (LP) [4] or plasma enchanced (PE) [5] CVD-methods.

Stripe waveguides are prepared by etching a ridge into the planar waveguides.

An alternative technique of waveguide fabrication is the doping of SiO_2 by phosphorus (PSG).

2.3. $LiNbO_3$

The lithium niobate technology, in which waveguides are formed typically by titanium indiffusion, is considered the most advanced and has provided most of the prototype devices for research systems demonstrations.

Typical diffusion conditions and resulting refractive index changes are given in Fig. 2 [6].

The propagation losses of single-mode Ti:$LiNbO_3$ stripe waveguides are very low ($\sim$0.2 dB/cm at $\lambda = 1.3$ μm) and the optical fields match well monomode fibres.

Another technique for fabricating waveguides in $LiNbO_3$ is the proton exchange [7].

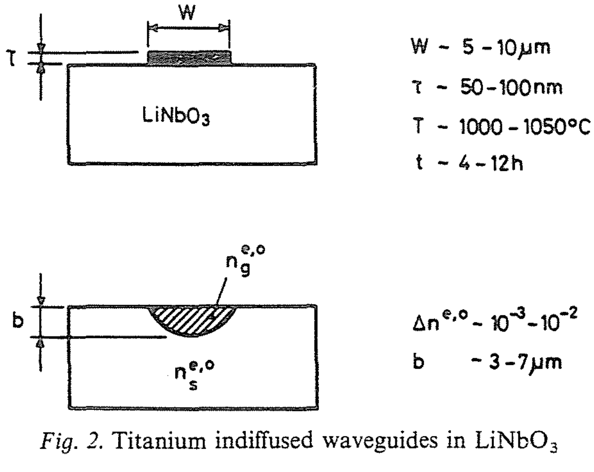

Fig. 2. Titanium indiffused waveguides in $LiNbO_3$

3. Integrated optical devices

Several low-loss multimode devices have been fabricated of *glass* using *I/E* process. These are

— Branching circuits [8]
— Star couplers (see Fig. 3) [9]
— Multi/Demultiplexers (see Fig. 4) [10]

A series of passive integrated optic components have been developed on *silicon* as substrate material: Fresnel lenses, mirrors, beam splitters, polarization dividers, polarizers [4]. These elements have been combined to build complex devices like a spectrum analyser [11], a displacement sensor [12] or an integrated-optic disc pickup device [13]. This last example, which is one of the most sophisticated integrated optic devices, is shown in Fig. 5.

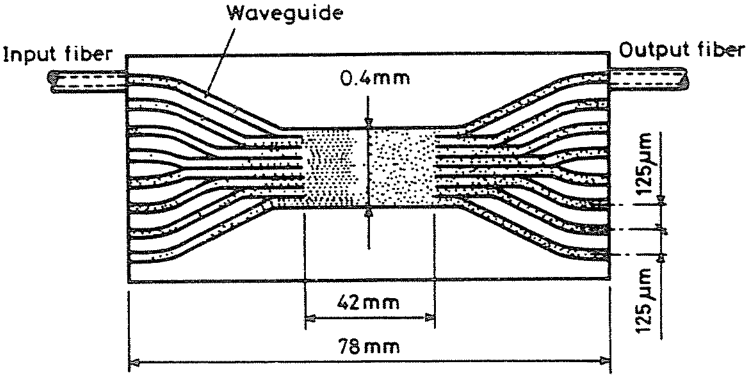

Fig. 3. Schematic drawing of an 8-port star coupler

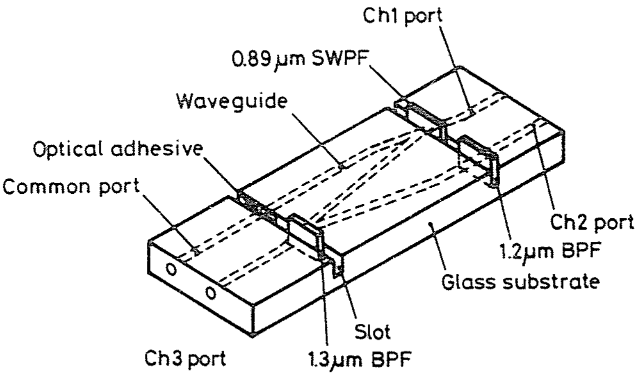

Fig. 4. Three-channel multi/demultiplexer: SWPF — Shortwavelength-pass filter; BPF — Bandpass filter

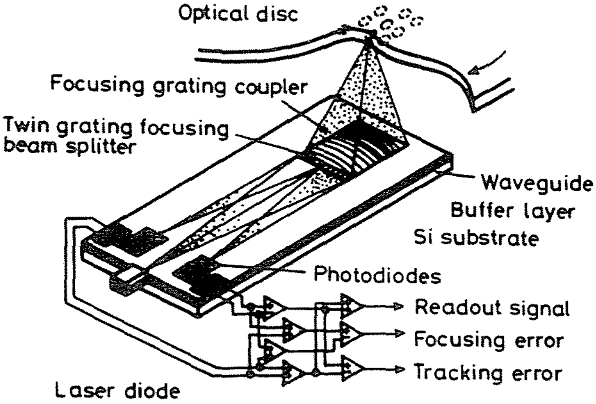

Fig. 5. Integrated optic disc pickup device on silicon

Here, the waveguide is performed by a sputtered glass layer, whereas the gratings are etched into a Si—N cladding layer.

A great variety of devices have been realized in *LiNbO*$_3$ which are summarized together with the main characteristics in [14]. Because of the large electrooptic coefficients, LiNbO$_3$ is specially suited for electrooptic functions.

Passive devices

— *Y*-branches
— Polarizers
— Polarization splitters
— Wavelength filters

Electro-optic devices

— Phase modulators
— Directional coupler switches
— *X*-switches
— Mach-Zehnder interferometric modulators
— Polarization transformers

Device characteristics

— Broad electrical bandwidth (>10 GHz)

— Low insertion loss (0.2 dB propagation loss, 0.15—0.3 dB coupling loss/interface)

— Low drive voltage (5—10 volts, single pol.)

4. Applications

Coherent lightwave systems are particularly well suited for application of integrated-optic devices because of the rich variety of optical control functions required. In addition to external modulators, electro-optic polarization controllers [14—17], frequency shifters [18], and adjustable couplers to build balanced mixers may add flexibility to the designs of coherent systems. All these devices have been demonstrated using integrated-optic techniques. Indeed, the possibility exists of integrating all these functions on a single chip to form an integrated coherent receiver [19].

In communication systems, IOC's will be used for external modulation of light and for optical switching. External modulation of light will be competing with direct modulation of diode lasers for market share. Since future lightwave systems are expected to operate at multiple gigabit-per-second rates, there is a strong effort to develop $LiNbO_3$-based external modulators.

Integrated optics technology has progressed rapidly in the last several years. The increasing number of industries involved in the commercialized of integrated optic products is indicative of the maturity of the IO-device technology and of its growing practical importance. One of the main areas, where IO is offering performance-enhancing benefits, is in fiber optic communication systems, including commercial telecommunications, military communications, and computer-to-computer data communication links. Further useful applications are expected in the fields of optical sensing, optical signal processing, and, possibly, optical computing.

References

1. Findakly, T.: "Glass waveguides by ion-exchange: a review", Optical Engineering, vol. *24*, pp. 244—250, 1985
2. Forrest, K., Pagano, S. J. and Viehmann, W.: "Channel waveguides in glass via silver-sodium field-assisted ion exchange" J. Lightwave Technol., vol. *LT-4*, pp. 140—150, 1986
3. Boyd, J. T., Wu, R. W., Zelmon, D. E., Naumann, A., Timlin, H. A.: "Planar and channel optical waveguides utilizing silicon technology", Proc. SPIE, vol. *517*, Integrated Optical Circuit Engineering I, pp. 100—106, 1984
4. Valette, S., Mottier, P., Lizet, J., Gidon, P., Jadot, J. P. and Villani, D.: "Integrated optics on silicon substrate: a way to achieve complex optical circuits", Proc. SPIE, vol. *651*, Integrated Optical Circuit Engineering III, pp. 94—99, 1986
5. Aarnio, J., Honkanen, S., Leppihalme, M.: "A novel semiconductor process for optoelectronic applications on silicon substrate", Proc. ECOC 87, Helsinki, Finland, 1987
6. Neyer, A., Pohlmann, T.: "Fabrication of low-loss titanium diffused lithiumniobate waveguides by using a closed platinum crucible" Electron. Lett., vol. *43*, 1987

7. Veselka, J. J., Bogert, G. A.: "Low-insertion-loss channel waveguides in $LiNbO_3$ fabricated by proton exchange", Electron. Lett., vol. *23*, pp. 265—266, 1987

8. Ikeda, Y., Okuda, E. and Oikawa, M.: "Graded-index optical waveguides and planar microlens arrays and their applications", Proc. EFOC/LAN 87, Basel, Switzerland, pp. 103—107, 1987

9. Okuda, E., Wada, H. and Yamasaki, T.: "Optical accessor and star coupler composed of planar gradient-index glass waveguide". Proc. 100C-ECOC 85, Venice, Italy, pp. 423—426, 1985

10. Seki, M., Sugawara, R., Okuda, E., Hanada, Y. and Yamasaki, T.: "Making a high performance guided-wave multi/demultiplexer by effective design considerations", Proc. OFC/IOOC 87, Reno, Nevada, paper TUK2, 1987

11. Valette, S., Lizet, J., Mottier, P., Jadot, J. P., Renard, S., Fournier, A., Grouillet, A. M., Gidon, P. and Denis, H.: "Integrated optical spectrum analyzer using planar technology on oxidized silicon substrate", Electron. Lett., vol. *19*, pp. 883—885, 1983

12. Lizet, J., Gidon, P., Valette, S.: "Integrated optics displacement sensor achieved on silicon substrate", Proc. ECIO 87, Glasgow, Scotland, pp. 210—212, 1987

13. Ura, S., Suhara, T., Nishihara, H. and Koyama, J.: "An integrated-optic disk pickup device", J. Lightwave Technol., vol. *LT-4*, pp. 913—918, 1986

14. Voges, E. and Neyer, A.: "Integrated-optic devices on $LiNbO_3$ for optical communication", J. Lightwave Technol., vol. *LT-5*, 1987

15. Alferness, R. C.: "Electrooptic guided-wave device for general polarization transformations", IEEE J. Quantum Electron., vol. *QE-1 7*, pp. 2225—2227, 1981

16. Alferness, R. C. and Buhl, L. L.: "Long wavelength Ti : $LiNbO_3$ waveguide electrooptic TE↔TM converter", Electron. Lett. vol. *19*, pp. 40—41, 1983

17. Thaniyavarn, S.: "Wavelength-independent, optical-damage-immune $LiNbO_3$ Te-TM mode converter", Opt. Lett., vol. *11*, pp. 39—41, 1986

18. Heismann, F. and Ulrich, R.: "Integrated-optical frequency translator with stripe waveguide", Appl. Phys. Lett., vol. *45*, pp. 490—492, 1984

19. Stallard, W. A., Beaumont, A. R. and Booth, R. C.: "Integrated optic devices for coherent transmission", J. Lightwave Technol., vol. *LT-4*, pp. 852—857, 1986

P. Richter H-1521, Budapest