# Basic tools for integrated optics

*Citation for published version (APA):*
Smit, M. K. (1990). Basic tools for integrated optics. In A. Driessen (Ed.), *Sensors and actuators : optical transducers ; proceedings S & A symposium, November 15-19, Enschede, The Netherlands* (pp. 175-189). Kluwer Technical Books.

*Document status and date:*
Published: 01/01/1990

*Document Version:*
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

*Please check the document version of this publication:*

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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# BASIC TOOLS FOR INTEGRATED OPTICS

**M.K. Smit**

**Delft University of Technology, Department of Electrical Engineering, P.O. Box 5031, 2600 GA Delft, The Netherlands, IN790, 13p, GVE690, BW790, TG.**

Integrated Optics is a rapidly developing technology. In this paper selected topics on material choice, elementary components and design methods for integrated optical circuits are discussed.

## 1 Introduction

In the past ten years the optical fibre replaced the copper-cable in communication links with a high traffic intensity (trunks). In the coming ten years it will do so in the local subscriber network. Each subscriber will then be equipped with one or more optical chips to do part of the signal processing. To be prepared for this development industrial as well as governmental research institutes are investing huge amounts of money in Integrated Optics research nowadays.

Figure 1 illustrates a future optical chip as it might be applied in a simple receiver. The chip is based on the coherent transmission scheme, which is discussed in more detail by Verbeek [this issue].

A number of components will have to be integrated monolithically on such a chip. In the example of figure 1 these are straight and bent waveguides, waveguide crossings, directional couplers, polarization splitters and controllers, a laser and detector diodes, and a few transistors for preamplification.

The monolithic integration of a circuit of the aforementioned complexity will take several years to become feasible. Current research is directed towards the development and improvement of planar components, with emphasis on fabrication

*A. Driessen (ed.) Sensors & Actuators, Optical Transducers.*

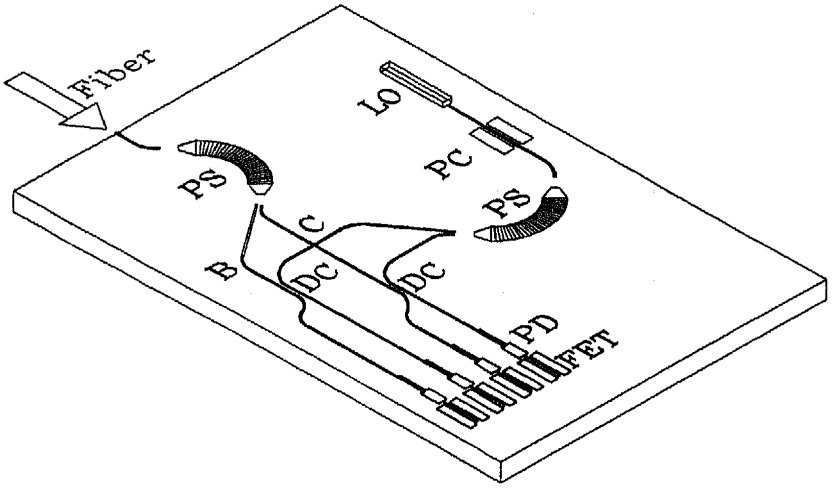

*Figure 1. Impression of a coherent optical receiver chip (LO = local-oscillator laser, PC = polarization controller, PS = polarization splitter, C = waveguide crossing, DC = directional coupler, B = waveguide bend, PD = photodiode and FET = field-effect transistor) (Drawing by Y.S. Oei, Delft University of Technology)*

schemes which allow for the integration of other components. Recent experiments are mostly restricted to the integration of two or three different components.

In this paper some aspects of the development of planar optical components and circuits will be discussed.

## 2 Components and circuits

### 2.1 Waveguides

The most elementary component in optical chips is the optical waveguide. Most optical components are based on waveguides. Further, waveguides are essential for interconnection. Roughly speaking, two classes of waveguides can be distinguished: low contrast and high contrast waveguides.

Optical fibres have a low refractive index contrast (typically less than $10^{-2}$) and moderate dimensions (typically 5-10 µm). For easy coupling from and to fibres the dimensions of the planar waveguide and its refractive index contrast have to be close to those of the fibre (field match). Low contrast waveguides are fabricated by deposition of doped glasses or by diffusion or ion exchange. A disadvantage of low-contrast waveguides is that they do not allow for short bending radii (typically centimeters) which is disadvantageous from a viewpoint of circuit miniaturization, and that it is difficult to couple them to lasers, which have small waveguide dimensions (0.5-2 µm) and a relatively high index contrast.

For high-contrast waveguides the advantages and disadvantages are just the other way around: easy coupling to lasers, short bending radii, complicated coupling to fibres. Monolithically integrated circuits will most probably be of the high-contrast type, because of the requirements imposed by the laser, and the importance of short bends for circuit miniaturization.

To keep waveguides monomode the dimensions have to be decreased with increasing contrast. High-contrast waveguides require a well-controlled sub-micron width (typically 0.5 µm or less) for monomode operation. Furthermore the waveguide edges have to be extremely smooth in order to keep scattering losses within acceptable limits. With the present state-of-the-art it is extremely difficult to meet these requirements, and a compromise will have to be accepted with respect to the maximum applicable index contrast.

## 2.2 Bends

Waveguide bends are applied for interconnection and as part of components (e.g. ring resonators). In low-contrast waveguides the most important feature of a bend is the radiation loss, which imposes a lower limit to the bending radius. In high-contrast waveguides the loss mechanism is more complicated. If the bending radius is reduced, the first phenomenon that will be observed is a shift of the field distribution towards the outer edge of the waveguide, a shift which will be accompanied with a reduction of the mode width. This transformation of the field distribution will cause mismatch losses at the junctions between straight and bent waveguides.

These losses can be reduced by adapting the width of the straight waveguide to the width of the field in the bent waveguide. The latter width only depends on the bending radius and the index contrast at the outer edge of the bend, if the width of the bend is chosen sufficiently large. The field will then be guided solely by the outer edge (Whispering Gallery Mode). By aligning the straight waveguide to the center of the field distribution in the bent waveguide, coupling losses can be reduced from more than one decibel (without adaption) to less than 0.1 dB per junction. Figure 2 shows an Electron-Microscope photograph of a straight waveguide which has been optimally aligned with respect to a short bend.

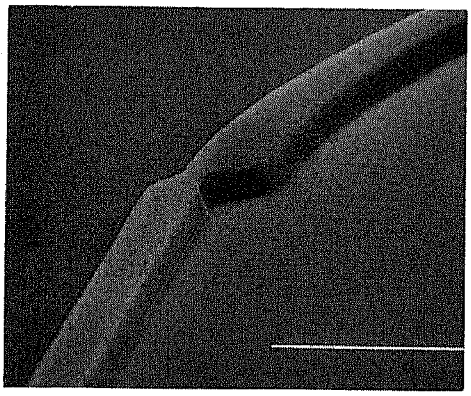

*Figure 2. Scanning Electron Microscope (SEM) photograph showing the adaption between a straight and a bent waveguide*

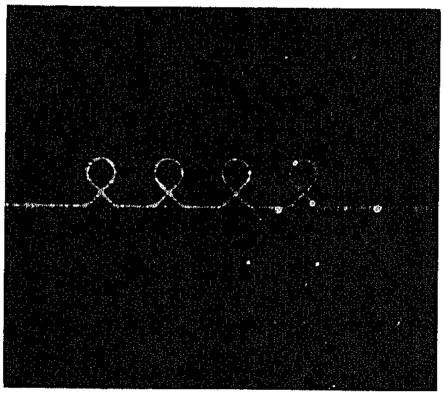

*Figure 3. Four loops with a bending radius of 150 µm, showing the potential of well-designed bends*

If the junctions between the straight and the bent waveguide sections are optimized, a lower limit to the bending radius is imposed by the fundamental radiation loss. In high-contrast waveguides this limit will be lower by more than one order than the limit imposed by the mismatch loss if no adaption is applied. Best results reported are a total loss of 0.2 dB/90° with R = 75 µm in $Al_2O_3/SiO_2$ waveguides at a wavelength of 1.3 µm, 0.6 dB/90° with R = 50 µm in $Al_2O_3/SiO_2$ "double-ridge" waveguides at a wavelength of 632.8 nm and 0.5 dB/90° with R = 150 µm in MOVPE-grown GaInAsP/InP ridge waveguides at a wavelength of 1.52 µm*.

## 2.3 Tapers and Y-Junctions

Tapers are used for smoothly connecting waveguides with different widths. They are designed on low transmission loss and short length. If the taper length is chosen to short, power will be converted from the fundamental guided mode to higher order guided or radiating modes. Ray theory provides a simple criterion for low-loss taper design: the taper angle should be chosen such that after reflection by the taper edge the propagation angle corresponding to the fundamental mode is closer to its original value than to that corresponding to the second order mode (the first order mode will not be excited in symmetrical configurations). From this criterion it is clear that in high-contrast waveguides, in which the ray-propagation angles are large, taper angles can be chosen large too and, consequently, taper lenghts can be much shorter than in low-contrast waveguides.

Y-junctions consist of a taper section, followed by a two-branch section, as depicted in figure 4. If the taper angle is chosen small enough a fundamental mode, coming from the left, will smoothly broaden and then be separated over the two branches

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* E.C.M. Pennings, "Bends in Optical Ridge Waveguides: modeling and experiments", Ph.D. Thesis, Delft University of Technology, Delft, 1990.

without much power loss. A well designed Y-junction can thus be used as a power splitter.

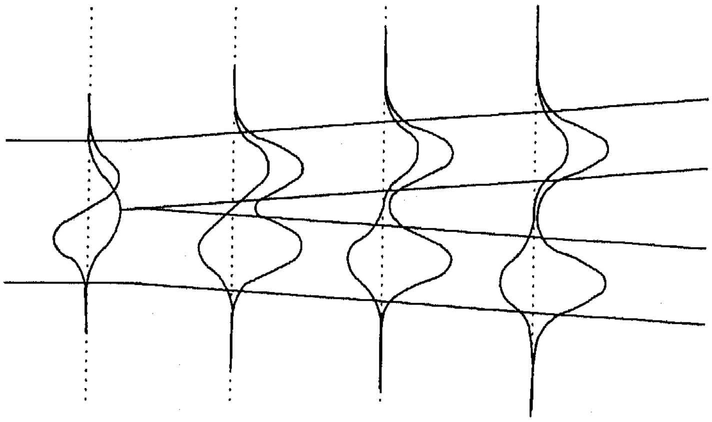

*Figure 4. Transformation through an Y-junction of the fundamental and the first-order mode into two in-phase and two anti-phase signals respectively (even and odd system mode)*

As a power combiner, its operation is more problematic, because the transmission behaviour is strongly dependent on the relative phase and amplitude of the signals in the two branches. If these signals are equal then, on reciprocity considerations, we may expect that they will transform gradually into the fundamental mode of the output guide, as shown in figure 4 in reverse direction. If the two signals have anti-phase, on the other hand, they will transform into the first-order mode. If the output waveguide is monomode this mode will radiate and the power loss will amount to 100%. If the two signals are uncorrelated the average power loss will amount to 50%. This makes the Y-junction less suitable as a power combiner.

## 2.4 Couplers

Figure 5 shows the fundamental operation of a conventional synchronous coupler. In such a coupler, which consists of two identical weakly coupled waveguides, power will be transferred periodically between the two waveguides. The distance at which all of the power is transferred to the other waveguide is called the coupling length. A coupler with half this length acts as a 3-dB coupler, in which the input power is equally divided over the two output ports. Any other coupling ratio can be obtained, in principle, by a proper choice of the coupler length.

A serious drawback of the conventional synchronous coupler is its extreme sensitivity to fabrication tolerance. The coupling length depends exponentially on the distance between the two waveguides, and a small difference between the two guides can seriously affect the coupling behaviour. Many experiments have shown that without a tuning or trimming facility the coupling ratio is unpredictable. Inclusion of such a facility considerably complicates coupler design and fabrication. Further, due to the weak coupling, the coupling length is large (typically many millimeters), which impedes circuit miniaturization.

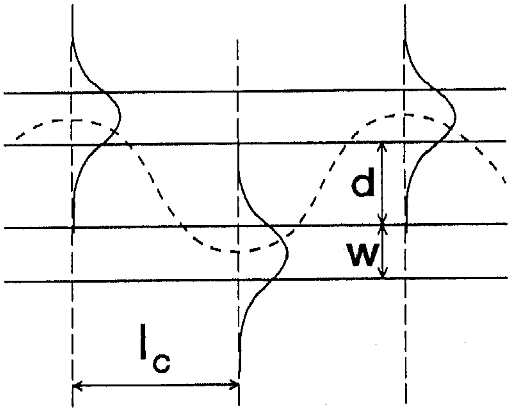

*Figure 5. Periodic power transfer in a synchronous directional coupler*

To reduce the aforementioned sensitivity other principles for power division, which are less sensitive to fabrication tolerances, are investigated. One possibility is a combination of reflection and transmission in an asymmetrical waveguide crossing.

At the Delft University research is focussed on the so-called Two-Mode Interference coupler. This coupler is a conventional coupler, in which the distance between the two waveguides is reduced to zero. The TMI coupler can thus be conceived of as two Y-junctions connected by a bimodal waveguide section. In this section there is a very strong coupling, which appears to be much less sensitive to fabrication tolerances. An additional advantage is that, due to the strong coupling, the coupling length and, consequently, the coupler length, is short. Coupler lengths shorter than 300 µm have been demonstrated. Insertion loss is slightly higher than for a conventional coupler, typically 0.5-1 dB.

## 2.5 Switches and modulators

A variety of principles can be applied for switching and modulation. Most of them are based on an electrically induced change in the optical properties of the waveguide material or its direct environment. Thermally, acoustically or magnetically induced changes have also been applied.

A frequently applied component is the synchronous coupler in which the refractive index of one or both of the parallel waveguides can be controlled electrically. If both waveguides are identical without an applied voltage, and the coupler is designed so as to transfer all power to the other waveguide (cross state), then application of a voltage to one of the waveguides will frustrate the synchronism, and all power will remain in the original waveguide (bar state). In this configuration the coupler can be used both as a switch and as a (digital) amplitude modulator. The sensitivity to fabrication tolerance is the same as for the passive coupler, but addition of tuning electrodes will now be possible without additional process steps. The length of this type of coupler is typically in the order of millimeters to centimeters.

Phase modulators can be constructed from a single waveguide in which the refractive index can be changed over a certain length. This can be done with the electro-optical effect (in electro-optical materials) or with carrier injection or depletion (in semiconductors). The latter effect does not only cause a change in the refractive index, but also in the optical absorption, so that the phase modulation will be accompanied with an amplitude modulation. The effects are so small that device lengths are typically many millimeters. Carrier injection allows for shorter device lengths, but at the cost of large inherent absorption.

In switching matrices device length is an important consideration in the design of the switch. For short switches other switching principles are investigated, a popular one being electrically or thermally induced total reflection of a guided wave. A problem in developing this type of switch is to keep the insertion loss low both in the cross and the bar state.

## 2.6 Sources and detectors

The laser-market is one of the first markets in opto-electronics that has become big business. Semiconductor lasers have developed from unstable sources with a broad spectrum to sources with very small linewidths, high output power and a GHz modulation bandwidth.

The development to ever smaller linewidths and greater output powers has not yet come to an end. Especially the event of coherent transmission poses extremely high requirements to the line-width of the laser. For homodyne detection linewidths in the order of 20 kHz are required, which is a relative linewidth of $10^{-10}$! These linewidths have been demonstrated experimentally for lasers with external cavities. A disadvantage of this approach is the cavity length, which amounts to several centimeters. Solutions are searched in two directions: releasing the linewidth requirements by applying intelligent modulation and detection schemes, and improving laser linewidth and stability.

Figure 6 shows the structure of a modern multi-section laser. This laser consists of three sections. The first section provides the gain which is necessary for laser operation. The last section contains a grating which, by its wavelength selective reflection coefficient, selects one single mode out of the spectrum of longitudinal modes, which can exist in the resonator. The intermediate section is used to modulate the optical length of the resonator, and thus provides a phase modulation capability. Linewidth of these laser types is typically 10 MHz, output power several milliwatts and modulation bandwidth more than 1 GHz. They will become commercially available within a few years.

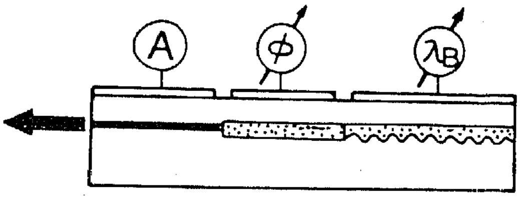

*Figure 6. Structure of a multi-section laser, consisting of a gain, a modulation and a grating section*

Detectors are less complicated than lasers. A planar detector consists of an absorbing waveguide, provided with electrodes to collect the generated electron-hole pairs. Research is directed towards reduction of the detector length (and, consequently, electrode capacitance) without reducing the detector efficiency. Further, much attention is paid to integration with transparent waveguide circuits on one side, and electronic components (FET's) on the other.

### 2.7 Integration

Integration is still in a premature stage. Integration of lasers with monitor-diodes, FET's or transparent waveguides has been reported. Integration of sophisticated lasers, such as the multi-section laser, with a number of the components discussed previously, will take many years. Yet integration is an essential step in reducing circuit cost, which is prerequisite to large-scale application of optical chips in local telecommunication networks.

## 3 Materials

### 3.1 Dielectric materials

For the realization of passive optical circuits a variety of materials, such as oxides, compound glasses, nitrides, fluorides and also polymers is available. For low-contrast waveguides Phosphorous doped $SiO_2$ on silicon substrate, with undoped $SiO_2$ as cladding material, is a popular waveguide system. Further, many experiments have been reported on compound glasses in which the index has been locally increased by ion-exchange. For high-contrast waveguides $Si_3N_4$ on silicon substrates, with $SiO_2$ as cladding material, is a popular combination because of its compatibility with silicon technology.

### 3.2 Electro-optic materials

For the realization of modulators, switches and polarization controllers two materials are available. In the class of electro-optic crystals, $LiNbO_3$ has been well developed and components as switches, modulators and even small switching networks are commercially available. Recently, polymers have been developed with electro-optic coefficients comparable to $LiNbO_3$. Within the framework of the RACE program the applicability of polymers for integrated optical components is being investigated. If the long term reliability of polymer components can be brought onto an acceptable level they will form a low-cost alternative to $LiNbO_3$-components.

### 3.3 III-V Semiconductors

III-V semiconductors allow for monolithic integration of complete optical chips, including sources and detectors, and electronic components. They also possess electro-optical properties, although the magnitude is smaller than in $LiNbO_3$. III-V semiconductors are therefore considered as the most promising materials for Integrated Optics. Research on these materials started with AlGaAs on GaAs substrate. For telecommunication, research has shifted to InGaAsP on InP substrates because these materials can emit and detect light at 1.3 and 1.55 µm, the wavelengths at which the fibre properties are optimal.

For data storage the wavelengths are shifting in the opposite direction because of the higher resolution at shorter wavelengths. With InGaAlP on GaAs substrate milliwatt powers at 670 nm wavelength have already been realized.

## 4 Design

With the increasing complexity of integrated optical circuits the need for design software is growing. At present CAD of integrated optical circuits is restricted to the level of mask-layout definition. The application of "silicon"-software poses problems for the design of optical circuits for two reasons. Firstly, generation of smooth bends is of little value in electronic circuits, and is problematic in most design programs. Further, the required accuracy (submicron) in relation to the size of the circuits (in the order of 1 cm), is a problem for the older software. Modern software can handle this problem, but is mostly tailored to orthogonal structures. The universities of Twente and Delft have therefore, in a common effort, developed software which meets the requirements of Integrated Optics. Recently the first professional program for generation of EBPG masks was announced.

The Delft University has started a project for adapting professional microwave design software to the design and analysis of integrated optical and opto-electronic circuits. There is a long way to go, however, before Integrated Optics CAD software will approach the sophistication of nowadays silicon software.

## 5 Conclusions

Integrated Optics research is entering the era of really integrated circuits. So far, with only a few exceptions, research was focussed on individual components. At the moment the efforts on integration of several components are exceeding the level of incidental experiments. The coming decade will show the emergence of really Integrated Opto-electronics. Large investments will be necessary, however, to develop the technology and the design and analysis tools to a level which allows for monolithic integration with acceptable yield and cost figures.

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