Application Note 053

Planar Lightguide Circuits: An Emerging Market for Refractive Index Profile Analysis

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1. Introduction

Over the past decade, optical waveguide components (OWC) in various materials have become available from a variety of manufacturers and vendors worldwide. These OWCs, which are now being deployed in commercial systems, can be active devices, such as advanced transmitters and modulators used in fiber-optic-based CATV and long-haul telecommunications systems, or passive devices, such as phase-arrays (phasars), Mach-Zehnder interferometer (MZI) switches, etc. The devices are based on planar optical waveguides, in which light is confined to substrate-surface channels and routed onto the chip. These channels are typically less than 10 microns across and are patterned using microlithography techniques. With appropriate optical circuits based on these channel guides, both passive functions (i.e. power splitting from one to several channels) and active functions (i.e. modulation) can be performed on the light. The primary materials used in the commercial market are glass or fused silica (bulk SiO_2 or SiO_2/Si) for passive devices and lithium niobate ($LiNbO_3$) for active devices. A closely related area, currently in the early R&D stage, is that of photonic integrated circuit devices, in which a variety of semiconductor optoelectronic devices are monolithically integrated and interconnected with waveguides. This article discusses glass and silica-based devices as well as how they are analyzed during the early stages of fabrication. An overview of emerging markets for integrated optics (IO) devices is also presented.

2. Silica Waveguide Devices

The most prominent feature of silica waveguides is their simple and well-defined waveguide structure. This allows photonics component manufacturers to produce multibeam or multistage interference devices such as arrayed-waveguide gratings (AWGs) and lattice-form programmable dispersion equalizers. A variety of passive planar lightwave circuits (PLCs), such as N×N star couplers, N×N AWG multiplexers, and thermo-optic matrix switches have been developed (see Fig. 1).

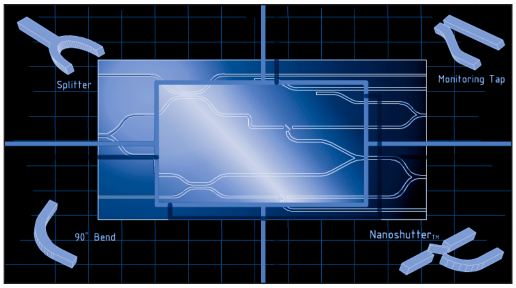

Figure 1. Various optical functions are performed using appropriate optical waveguides (courtesy of Nanovation Technologies).

PLCs using silica-based optical waveguides are fabricated on silicon or silica substrate by a combination of flame hydrolysis deposition (FHD) and reactive ion etching (see Fig. 2). Fine glass particles are produced in the oxyhydrogen flame and deposited on the host substrate (Si or SiO_2). After undercladding and core glass layers are deposited, the wafer is heated to high temperature for consolidation. The circuit pattern is fabricated by means of photolithography and reactive ion etching (RIE). Finally, core ridge structures are covered with an overcladding layer and consolidated again.

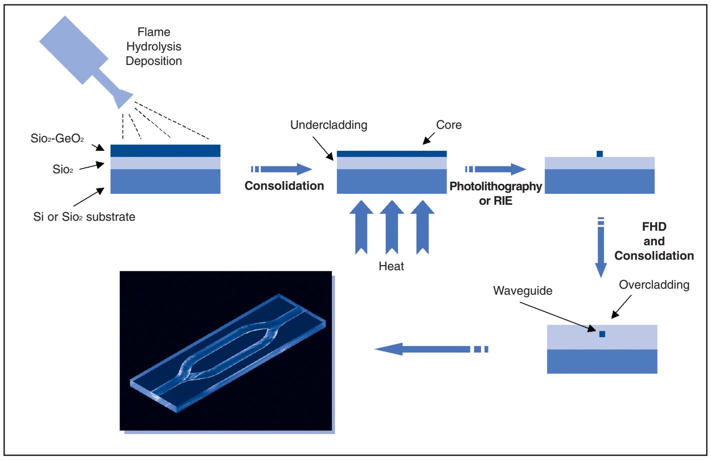

Figure 2. Planar waveguide fabrication technique

Since the typical bending radius R of a silica waveguide is between 2 and 25 mm, the chip size of the large-scale integrated circuit (IC) becomes several square centimeters. Therefore, propagation loss reduction and uniformity of refractive indices and core geometries throughout the wafer are essential. Propagation loss of 0.1 dB/cm is obtained in a two-meter long waveguide with Δ = 2% index difference (R = 2 mm) and loss of 0.035 dB/cm is obtained in a 1.6-meter long waveguide with Δ = 0.75% index difference (R = 5 mm). Table 1 summarizes the parameters and propagation characteristics of four typical kinds of waveguides. The propagation losses of low-Δ and medium-Δ waveguides are about 0.01 dB/cm, while high-Δ and superhigh-Δ waveguide losses are about 0.04 dB/cm and 0.07 dB/cm, respectively. The low-Δ waveguides are superior to the high-Δ waveguides in terms of fiber coupling losses with standard singlemode fibers. On the other hand, the minimum bending radii for high-Δ waveguides are much smaller than those for low-Δ waveguides. As a result, high-Δ waveguides are indispensable in constructing highly integrated and large-scale optical circuits such as N×N star couplers, AWG multiplexers and dispersion equalizers.

Different types of devices can be manufactured to suit various applications. Below is a list of the most popular IO devices:

		Waveguide		
Characteristics	Low-Δ	Medium-Δ	High-Δ	Superhigh-Δ
Index difference (%)	0.3	0.45	0.75	1.5 – 2.0
Core size (µm)	8×8	7×7	6×6	4.5×4.5 – 3×3
Loss (dB/cm)	<0.01	0.02	0.04	0.07
Coupling loss (dB/point)	<0.1	0.1	0.4	2.0
Bending radius (mm)	25	15	5	2

Table 1. Waveguide parameters and propagation characteristics of four kinds of waveguides

- N×N star coupler used in high-speed, multiple-access optical networks
- Arrayed-waveguide gratings (AWGs) (see Fig. 3) used to increase the aggregated transmission capacity of single-strand optical fiber
- Flat spectral response AWGs
- Uniform-loss and cyclic-frequency (ULCF) AWGs
- Athermal AWGs
- Phase error compensated (PEC) AWGs
- Optical add-drop multiplexers
- N×N matrix switches
- Lattice-form programmable filters

For technical details on PLC devices, E. Murphy's book[1] on integrated optics devices is recommended.

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[1] Edmond J. Murphy, *Integrated Optical Circuits and Components: Design and Applications.* New York: Marcel Dekker Inc., 1999.

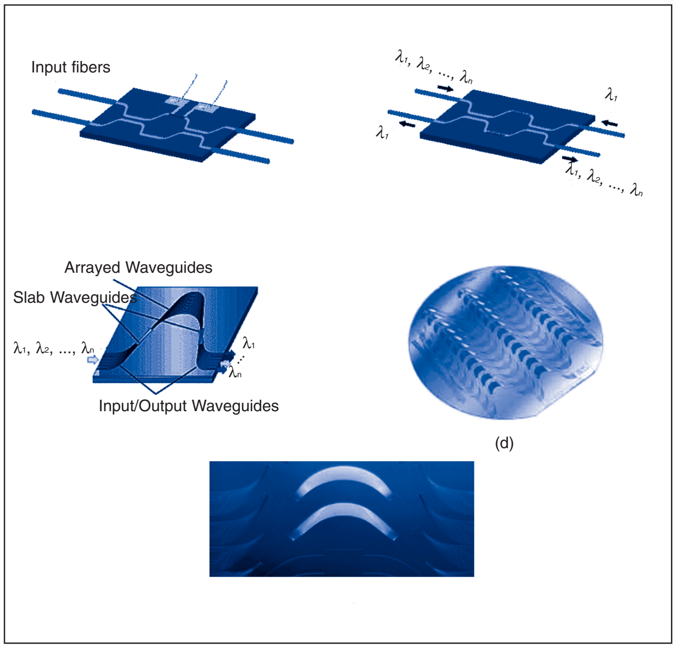

Figure 3. Examples of popular waveguides: electro-optic 2×2 switch (a), optical add-drop multiplexer (b), optical AWGs (c), SiO_2 AWGs on Si wafer (d) – (courtesy of Lightwave Microsystems Inc.), and detailed view of two SiO_2 phasars (e)

3. Material and Deposition Technology Choice

Bulk silica (SiO_2) and silica-on-silicon (SiO_2/Si) are by far the most common materials used to manufacture PLCs, due to their refractive-index match with silica-based optical fiber. Two major types of deposition processes are used today: chemical vapor deposition (CVD) and flame hydrolysis deposition (FHD). The CVD approach, which is a modification of standard semiconductor-processing techniques, is compatible with both clean-room processes and high-volume wafer production (in which more than 100 wafers can be simultaneously loaded in deposition chambers). A raised refractive index is created in the core-guiding region by the addition of phosphorus, germanium, or both, during the deposition process. Photolithography technology and reactive ion etching (RIE) are then used to pattern the waveguides.

The FHD deposition process (briefly introduced in section 2) is different from the CVD approach. Glass precursor chemicals are introduced into a hydrogen/oxygen torch in which a flame hydrolyzes the chemicals to form the appropriate glass composition (see Fig. 2). Glass particles (roughly 0.1 µm in diameter) are deposited onto the substrate (SiO_2 or Si) in a thick, porous and fluffy layer. Finally, this fragile structure is placed in a furnace and heated to consolidate the porous layer into a solid, clear glass layer free of bubbles or any other defects. The waveguides are then patterned using standard photolithography and RIE.

From a production standpoint, the use of silica waveguides has a number of significant advantages. An index of refraction roughly equal to that of optical fiber minimizes losses at the fiber-chip interface. The CVD process is also mature and allows low-cost volume production using a wafer-processing technology similar to the one developed for the semiconductor industry. The large dimensions of AWG devices (typically 1×3 cm) make it imperative that optimal clean-room conditions be maintained in order to avoid incorporation of unwanted particles. In that respect, CVD processing has an immense advantage. The main drawback of silica waveguides is the limited range of refractive-index differences, which ultimately restricts the reduction in size of individual devices.

Silicon and silicon-oxynitride (SiON) can also be used to form the lightguide material. A key benefit is the use of advanced process technologies originally developed for the semiconductor industry. Automated assembly techniques can be used to integrate passive devices with active components such as lasers or photodetectors, creating low-cost integrated devices. Furthermore, very-high-contrast waveguides can be made from these materials. This allows tight-bend radii and hence the possibility for compact integrated devices. However, due to the large refractive-index difference at the waveguide-fiber interface, propagation losses and coupling efficiencies constitute challenges for products based on silicon.

4. Refractive Index Profiling of Planar Waveguides

The refractive index profile (RIP) of the waveguide core plays an important role in characterizing the properties of the planar waveguide. It allows the determination of the guide's numerical aperture (NA) and of the number of modes propagating within the light guide core, while defining intermodal and/or profile dispersion caused by the lightguide itself. Furthermore, since the impulse response and, consequently, the information-carrying capacity of the waveguide is RIP-dependent, it is essential for PLC manufacturers to produce controlled waveguide profiles with great accuracy. Accurate knowledge of the RIP allows IO designers to reduce optical waveguide device manufacturing costs through tight control of the planar lightguide fabrication processes during the R&D phase. As a result, there is a need for accurate waveguide RIP measurement. Until now, however, there has been no refractive index profiler commercially available to PLC manufacturers. This is problematic: manufacturers without a refractive index profiler are rather like chefs without a sense of taste. They have been manufacturing PLCs using secret recipes without being able to analyze them before the devices are fully packaged. This has had a major negative impact on productivity and yield. Indeed, if a device fails the end-of-chain analysis, the energy and time spent on its fabrication and packaging are wasted and throughput decreases dramatically, resulting in a low-yield manufacturing scheme. A few of the companies involved in PLC manufacturing have in-house optical setups that allow waveguide RIP analysis. However, these setups are usually bulky and difficult to use.

Recently, the world's first Optical Waveguide Analyzer, the EXFO OWA–9500, has become available commercially. The OWA–9500, with its refracted near-field (RNF) approach, helps planar waveguide developers and scientists accurately control and optimize the PLC manufacturing process at a very early stage, increasing production yields.

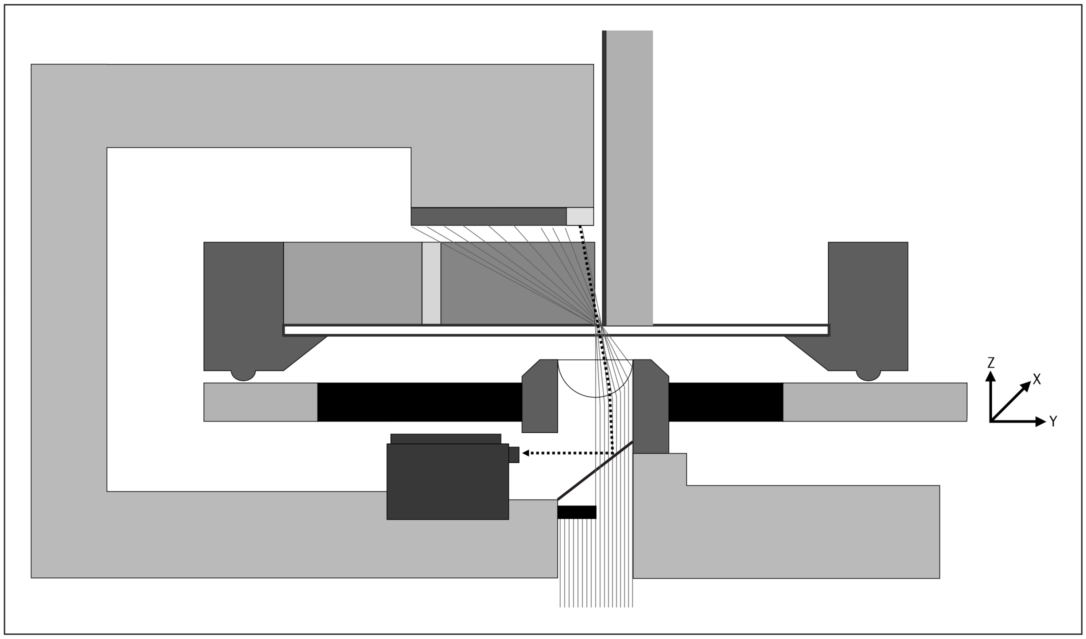

Figure 4. The refracted near-field (RNF) technique is used to measure the RIP of the waveguide.

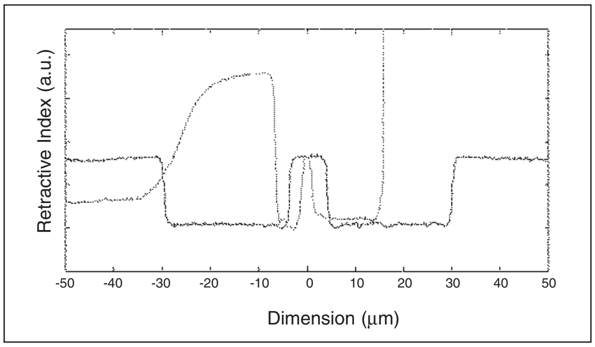

Figure 5. X–Y scans across the 10×2 µm² waveguide, showing its RIP. The refractive index scale has been set to an arbitrary unit to protect proprietary data.

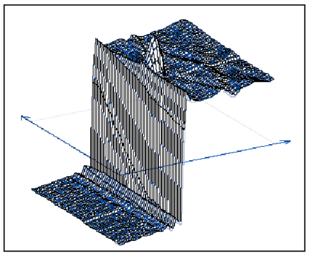

Figure 6. X–Y raster scan of a waveguide showing a 3-D refractive index profile, where the refractive index is plotted as the third dimension.

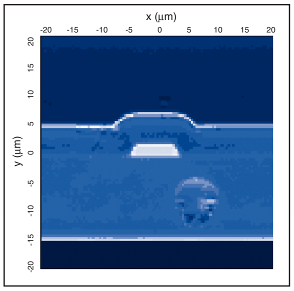

Figure 7. MatLab™-processed sectional raster scans of the 10×2 µm² SiO₂ waveguide. An air bubble, causing a defect in the undercladding, can be seen in the lower right corner of the figure.

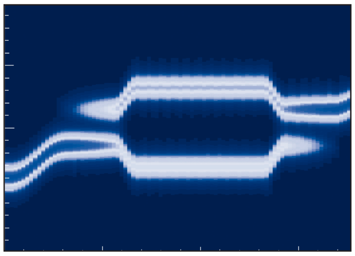

Figure 8. BPM simulation shows the electro-optical behaviors of a Mach-Zehnder interferometer (MZI) optical switch.

4.1. Principles of Operation

As shown in Figure 4, a collimated light beam emitted by a laser source is precisely focused, in the smallest spot size possible, on the end-face of the waveguide under test (WUT). The RNF source is typically a laser with a wavelength ranging from 630 nm to 850 nm. The shorter the RNF laser wavelength used, the higher the spatial resolution obtained. EXFO's OWA–9500 uses a long-life, 655 nm, temperature- and power-controlled laser diode for optimum RNF performance, providing a spatial resolution below 0.7 µm. The WUT end is placed vertically in a test cell. The test cell is scanned in 0.1 µm steps in x-y directions across the RNF laser beam, focused by a high-numerical-aperture (NA) immersion objective lens. The z direction allows the laser beam to be focused accurately on the WUT endface. The silicon detector placed above the sample endface collects the portion of the beam refracted out of the WUT. The detected signal is inversely proportional to the changes in the index of refraction encountered at the WUT end during a scan across the focus of the RNF beam. From the known refractive index values of the two reference blocks, a linear interpolation provides the sample's RIP (see Fig. 5).

Using the OWA–9500 3-D raster scan capability (see Fig. 6), a 3-D view of the WUT's refractive index profile is obtained and a contour analysis can be performed. The 3-D raster scan is not useful in itself; however, it can be sliced at different refractive index levels to provide topographic and geometric measurements of the WUT (see Fig. 7). Topography data can be downloaded to any simulation software using the beam propagation method (BPM) to simulate the various electro-optical behaviors of the device being tested (see Fig. 8).

5. An Emerging Market

Integrated optics applications have historically been niches of the analog/digital (A/D) and sensor fiber-optic markets. At present, however, major new markets are emerging. The largest of these is, perhaps, the telecommunications industry, which uses IO devices for multigigabit bidirectional communication data transmission, signal splitting and loop distribution. A second new market is CATV, where IO modules will be used for external modulation in fiber-optic-based signal distribution systems. In both telecommunications and CATV, IO devices enable signal transmission at higher data rates over longer distances. Instrumentation constitutes the third growing market with fiber-optic gyroscopes as the major application. High-speed telecommunications and fiber gyro applications are common to both the U.S. and Japanese markets today. In the United States, there is great interest in CATV and other analog fiber-optic link applications of IO technologies. In Japan, NTT's push for fiber-to-the-X (FTTX) is driving telecommunications loop applications. A forecast study of IO modulators performed by the Optoelectronics Industry and Technology Development Association (OIDA) predicts an average 24% annual growth rate in North America over the 1993–2003 period. The forecasted annual sales by 2003 amount to nearly US$200 million for fiber gyroscopes, while the photonics market enabled by IO modulators is many times larger and will exceed US$1 billion.

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