Chapter

Introductory Chapter: Electromagnetic Propagation and Waveguides in Photonics and Microwave Engineering

Patrick Steglich

1. Introduction

Waves can propagate as spherical waves in open space. In this case, the power of the wave decreases with the distance from the source as the square of the distance. In contrast, a waveguide can confine the propagating wave in such a way that the wave propagates only in one dimension. Assuming ideal conditions, the wave is not losing power while it propagates inside the waveguide.

Waveguides play a major role for applications in communications and sensing technologies. The theoretical understanding and practical investments are crucial to develop future innovations.

In photonics, two major types of waveguides can be distinguished, namely optical fibers and integrated waveguides. Waveguides in photonics operate typically in the visible and infrared light spectra.

Optical fibers are used for data transmission, as fiber lasers, for flexible transmission of laser radiation or for lighting, for sensor applications or decoration purposes [1]. The main application of optical fibers, however, is their use in telecommunication systems, making our daily life easier by a fast internet connection [2]. Other important technical applications of optical fibers are lasers [3], interferometers [4, 5], amplifier [6], and sensors [7]. The latter is important since it allows the detection of magnetic fields [8], humidity [9], temperature [10], and biological molecules [11, 12]. Massive research investments in the field of optical fibers [13–15] have led to novel applications. One important example is the use of optical for endoscopic applications [16, 17]. Also the fiber core has been modified (**Figure 1**), so that novel applications such as gas sensor can be addressed.

Integrated waveguides confine light in submicrometer structures on chip. Such waveguide structures are made either by doping the substrate material or by structuring it with etching procedures. Mostly, such waveguides are formed by patterning semiconductor materials like silicon, which is known as photonic integrated circuit technology [18]. The dimension of those waveguides in single mode operation is typically about 220 nm in width and 500 nm in height. **Figure 2** shows three different types of waveguides based on silicon.

The main applications are electro-optical modulators in telecommunications [19] and integrated sensors [20, 21] for point-of-care-diagnostics, environmental monitoring, or food analysis [22, 23]. A relatively novel approach is the silicon-organic hybrid technology [24–26]. Here, the silicon-based waveguide is covered with organic materials [27–29] leading to highly energy-efficient modulators [30] with large 3-dB

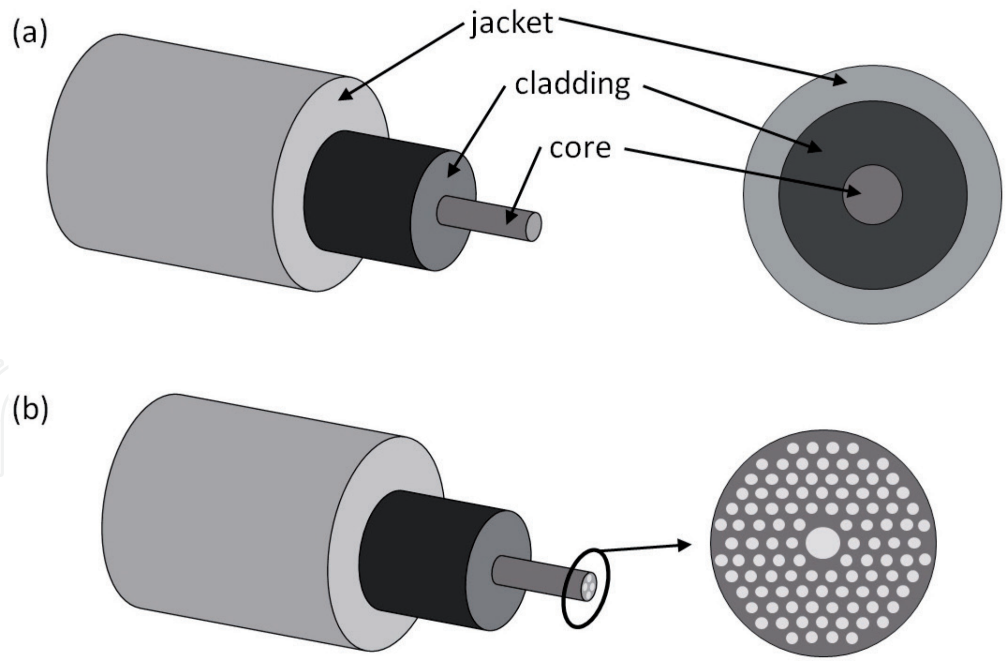

Figure 1.
Optical fiber with simple homogeneous fiber core (a) and with photonic crystals, also known as hollow core fiber (b).

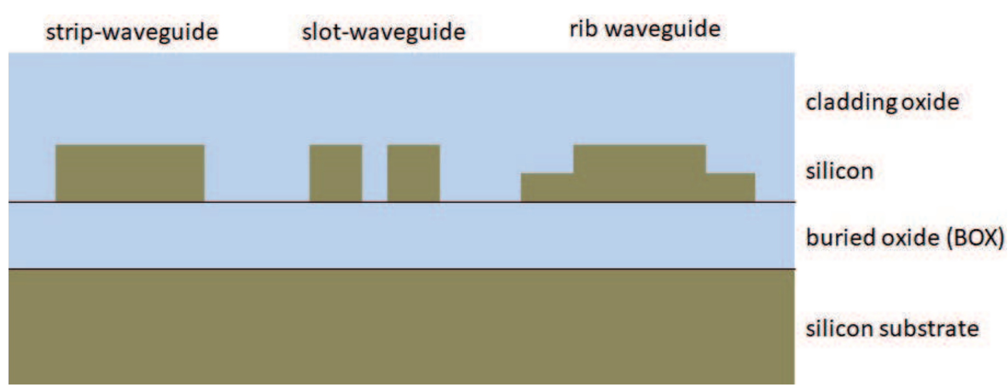

Figure 2.
Integrated optical waveguides based on silicon used in photonic integrated circuits.

modulation bandwidth [31]. This technology mainly uses slot waveguides because they provide a large overlap of optical and electrical field. Novel waveguide structures like slot waveguides [32–35] allow also the use of the quadratic electro-optical effect [36–38] and the electric field-induced linear electro-optical effect [39–40]. This gives perspective to novel modulation schemes and applications in programmable photonics.

Before optical waveguides were integrated into semiconductor chips, metal lines were already implemented several years ago, forming microwave waveguides [41]. These waveguides are used in microwave engineering. The short wavelengths distinguish microwave engineering from electronics. One particular example of microwave waveguides is the so called hollow metal pipe. A hollow metal pipe is a waveguide for electromagnetic waves, typically in the frequency range from 1 to 200 GHz [42]. Such waveguides are metal tubes with a generally rectangular, circular, or elliptical cross section. They have been studied and applied to industrial applications since almost one century [43]. New fabrication methods like 3D printing led to a renewed attention on this type of waveguide [44]. For example, practical work on microwaves concentrated on the low frequency end of the radio spectrum because it allows a long-range communication [45].

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