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REVIEW ARTICLE

Optical devices based on multilayer optical waveguide

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Abstract Optical waveguide is used to guide the transmission of light. This paper reviews multilayer optical waveguide and some devices based on it. The optical waveguide can be divided into single-layer and multilayer optical waveguides in general. Here, multilayer cylindrical waveguide and multilayer planar waveguides were mainly focused. The analyzing method and the structures of waveguides were also demonstrated in briefly. Both these multilayer optical waveguide used in different kinds of optical devices including optical modulator, laser, optical amplifier, optical switch and special fiber were further presented. At last, the principle and structure of these multilayer optical devices were compared.

Keywords multilayer waveguide, optical devices, multilayer structure

1 Introduction

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. It was first referred to as "light piping" in 1880 by Wheeler, which is known as optical fiber [1]. Rectangular dielectric waveguides were first studied theoretically by Schlosser in 1964 and Miller created the term "integrated optics" in 1969 [1]. The waveguide is mainly about optical fiber, film waveguide and strip waveguide. The optical fiber can be used in modulator, laser, transmission and characteristic compensation, etc [2,3]. Also, the film waveguide and the strip waveguide can be made into the active and passive optical waveguide components, such as modulators, optical switches and optical couplers [4].

There are some advantages of multilayer optical waveguide, such as perform better in the application of transmission characteristic, dispersion compensation, cut-off wavelength, etc; various kinds of structures of optical devices; diverse parameters result from the multilayer structure can be adjusted reasonable to different real applications. There are also some disadvantages as followings: complicated structures, manufacture craft and higher equipment requirements; numerical analysis is more complex than single-layer waveguide. Therefore, this paper mainly reviews the fundamental theories, constructions and applications of optical devices based on multilayer optical waveguide, which have been extensively applied in current study. And the guide wave theory and technology have been used to improve the performance of various optical devices and optical instruments.

2 Multilayer optical waveguide

Multilayer optical waveguide, as the name suggests, is a waveguide which is made up of several medium layers. It can be divided into multilayer cylindrical waveguide and multilayer planar waveguide. These waveguides although have different constructions, both of the analysis are from the Maxwell equation and Helmholtz equation which based on optical waveguide theory and electromagnetic field theory.

The structure of the multilayer cylindrical waveguide in cylindrical coordinate is shown in Fig. 1.

This fiber is different from common fiber for the different refractive index in each cladding resulting from various materials. But the method of analysis is the same as common fiber. It can be analyzed by vector method or scalar method. However, both methods serve to the solving of the propagation constant β and the cut-off condition. The basic thinking is that [5]: at first, using the wave equation to yield modal fields; and then, working out the characteristic equation according to the condition of boundary continuity; finally, getting the cut-off condition, away from the cut-off condition and the propagation constant β when the $W \rightarrow 0$ or $V \rightarrow \infty$ in the characteristic equation. In the process of solving multi-cladding fiber's characteristic equation, we can use the transmission matrix method [6].

For the multilayer planar waveguide, it has widely

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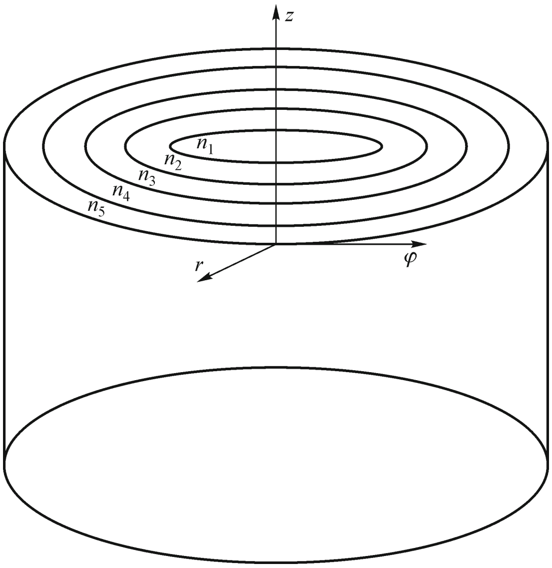

Fig. 1 Structure of 5-cladding fiber in cylindrical coordinate

application in optical devices; and the number of layers as well as other dimension parameters in practical application are based on the demand.

The basic structure of multilayer planar waveguide is shown in Fig. 2.

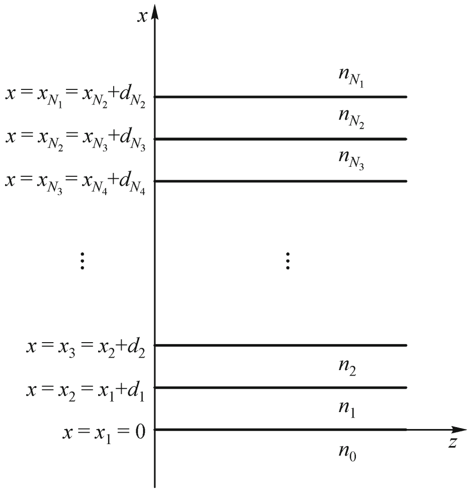

Fig. 2 Basic structure of multilayer planar waveguide

As shown in Fig. 2, multilayer planar waveguide has different refractive index in different layers; and the total number of layers is N ($N = 3, 5, 7\ldots$). The light propagates along the z direction. The cladding and substrate layers are assumed to extend to infinity in the $+x$ and $-x$ directions, respectively. The d_i is used to denote the width of i-th layer and the n_i stands for the refractive index in the same layer [7].

Kuo et al proposed a general method for analyzing a multilayer optical waveguide with all nonlinear layers in Ref. [7]. Analyzing the multilayer optical planar waveguides with photonic meta-material, the multi-branch optical waveguide structure with all nonlinear guiding films had been demonstrated in Refs. [8] and [9], respectively.

All above basic multilayer waveguide can be used in all kinds of optical devices in Section 3. But there are some different results from the different foundations and performances of devices.

3 Multilayer optical waveguide devices

3.1 Optical modulator

With the fast development of optical communication, the optical modulator becomes one of the most useful optical devices. The principle of optical modulator is that the change of phase, amplitude, frequency or the polarization state is achieved by physical effects such as electro-optic (EO) effect, acousto-optic (AO) effect in order to modulate an original signal on the optical one and then to output it. Multilayer optical modulator can be a multilayer optical fiber or a multilayer waveguide.

Multilayer EO modulator based on fiber grating is shown in Fig. 3.

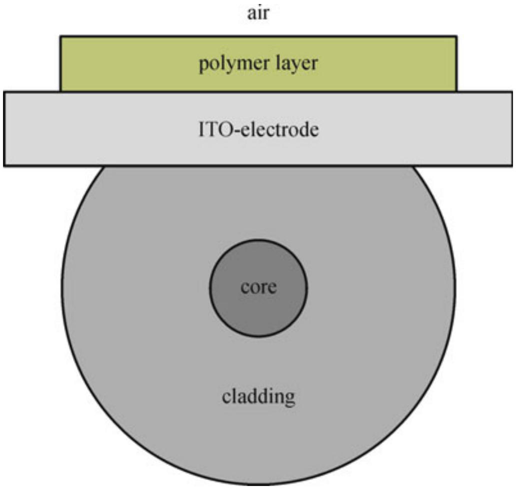

Fig. 3 Four-layer uniform circular waveguide structure. ITO: indium tin oxide

This modulator includes three parts: the fiber grating, the indium tin oxide (ITO) electrode and polymer film. These parts have different refractive index and EO coefficient. The working principle is that an organic polymer film is coated in the fiber grating making polymer material with high EO coefficient, which change the resonant wavelength of fiber grating modulator [10,11].

According to the knowledge of fiber grating, we can get the resonant wavelength:

$$\lambda_{\max} = (N_{\text{eff1}} - N_{\text{eff2}})\Lambda. \tag{1}$$

The N_{eff1}, N_{eff2} represent the epffective refractive index in core and in cladding, respectively. From Eq. (1), the resonant wavelength of grating modulator depends on the grating period and the relative refraction index.

What's more, the modulator can be influenced by the thickness of lapping cladding and polymer film and the kinds of polymer. Determining some parameters and changing some parameters can be used to optimize the performance of multilayer fiber grating modulator [10].

Multilayer optical modulator also can be made by multilayer planar waveguide. Figure 4 shows the structure of a polymer modulator.

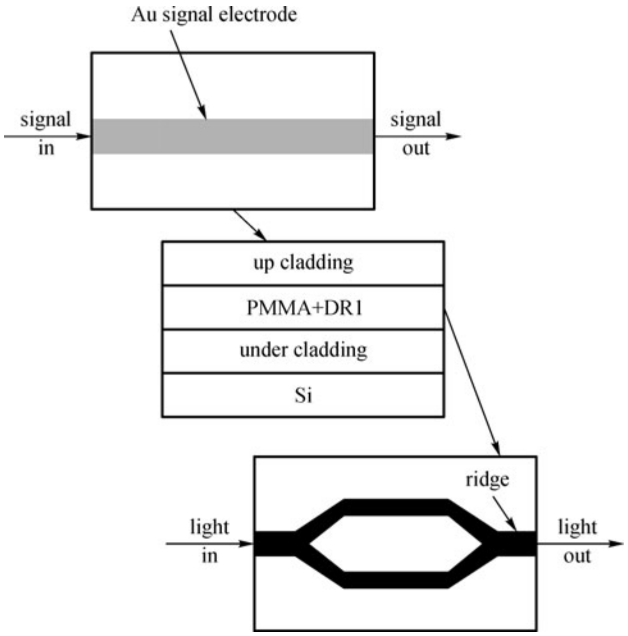

Fig. 4 Structure of a polymer modulator. PMMA: polymethylmethacrylate, DR1: disperse red 1

In this modulator, the modulation region of Maher-Zehnder interferometer (MZI) is between under cladding and up cladding. Gold (Au) electrode is on the first layer; and silicon (Si) is used as substrate. A low loss optical modulator based on the passive waveguide instead of the active waveguide in the non-modulation region in order for reducing the propagation loss, but this modulator has a more complicated fabrication process on multilayer waveguide. Based on modulating in cladding, Ref. [12] demonstrated an EO polymer modulator to reduce the propagation loss while not increase the complexity of fabrication process.

3.2 Laser

The laser's performance is important for the optical communication system. With the development of fiber fabrication process and semiconductor laser technology, such as the significant improvement of oscillation wavelength range, coordination of wavelength and threshold etc, the laser based on fiber has been laser's new technology.

Figures 5 and 6 are the schematic diagrams of structure of double-clad fiber (DCF) laser [3] and rare earth doped DCF laser [3], respectively.

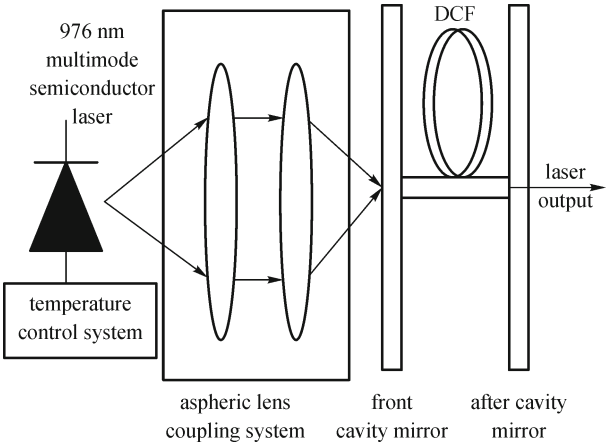

Fig. 5 Schematic diagram of structure of DCF laser

The pump light beam generated from pump source is collimated at the first lens and combined together through the second one in aspheric lens coupling system. The light beams travel in the inner cladding through a dichroic mirror at the front end of double-clad fiber. As light beam traveling along the double-clad fiber, rare earth ions doped in fiber core have the inversion distribution due to the stimulated transition of active ions. Meeting the condition of laser oscillation, the laser beam is outputted at the other side of fiber.

This DCF laser [3] has some properties follows: the silicon dioxide (SiO_2) doped rare earth element can be used to make up the core of fiber, which is the channel for laser oscillation. And the channel is single-mode for related wavelength; the refractive index in inner cladding is lower than that in the core of fiber as the transverse size and numerical aperture are large and the pump light transfer along the inner cladding; the refractive index in outer cladding is lower than that in the inner cladding; protective layer surrounded by hard-plastic to protect the fiber.

In the practical application, the laser also can be obtained by double Bragg grating. The Yr-doped DCF laser based on microstructure fiber (MOF) has better performance. The core of the double-clad Yr-doped fiber laser is the channel of signal light, meanwhile the pump light beam transfers in the inner clad [13]. It is demonstrated that a tunable Er^{3+}/Yb^{3+} co-doped fiber

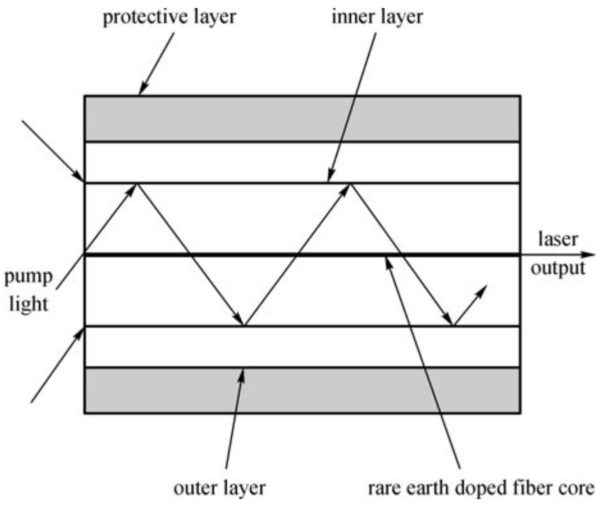

Fig. 6 Schematic diagram of rare earth doped DCF laser

laser with a narrow line width less than 0.08 nm has been achieved using a diffraction grating for wavelength selection [14].

3.3 Optical amplifier

While the optical signal traveling in fiber, the loss power of signal light and light-pulse broaden by chromatic dispersion will be happened. Therefore, it is necessary to set a repeater per meters to amplify, regenerate and then transfer the signal light. In addition, amplifying and processing the signal light straightly result in improving the application of optical amplifier.

Figure7 shows the basic process of optical amplification. Optical amplification is based on the interactions among signal light, pump light and gain medium. The power of pump light is transformed to the power of signal light and output.

For optical waveguide amplification, we can use the double-clad optical fiber, channel waveguide, inverted ridge waveguide, etc. As for the double doped fiber amplifier, the foundational principle is the same as DCF laser, and it is excepted that there is other light — signal light, in the optical amplifier. For avoiding the problem of etching materials in polymer waveguide, we often use an inverted ridge waveguide [15,16], as shown in Fig. 8.

The substrate of this optical amplifier is Si, the under cladding can be Si or SiO_2. It should be noted that, the cladding layer cannot be etched too much when taking the Si as the under cladding. The waveguide core is polymer and the up cladding can be Si or SiO_2. The thickness of cladding should be appropriate to avoid more propagation loss.

The theoretic research of optical amplifier based on long-period fiber grating and the characteristic analysis of Er^{3+} doped waveguide amplifier have been introduced in Refs. [17] and [18], respectively.

3.4 Optical switch

Based on propagation manner, we classify optical switches into guided wave optical switch and space optical switch. Also, there are different kinds of optical switches depend on physical effects, such as electro-optic switch, thermo-optic (TO) switch [19], acousto-optic switch, and semiconductor optical amplifier (SOA) switch.

The following example is MZI-TO switch based on TO switch, and its structure is shown in Fig. 9.

This TO switch is made up of Si-substrate, under cladding, up cladding and the pole. In this optical switch, the performance of cladding has an influence on the function of switch. Taking the SiO_2 as under cladding is to improve the response speed of TO switch and taking Si with a good endothermic performance as substrate is to stabilize the temperature of the under surface of under cladding. If the refractivity difference between the core and the polymer is large, it will result in a thinner up cladding.

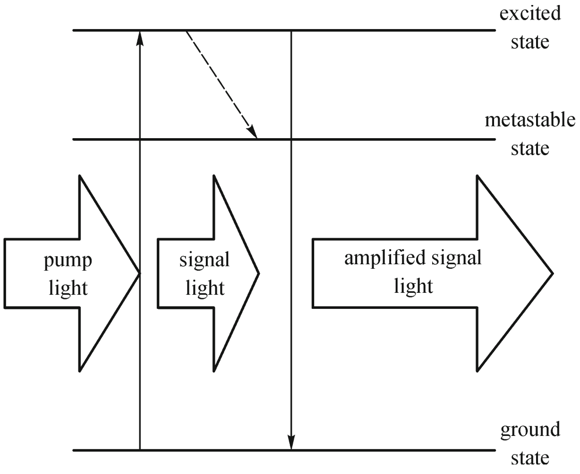

Fig. 7 Basic process of optical amplification

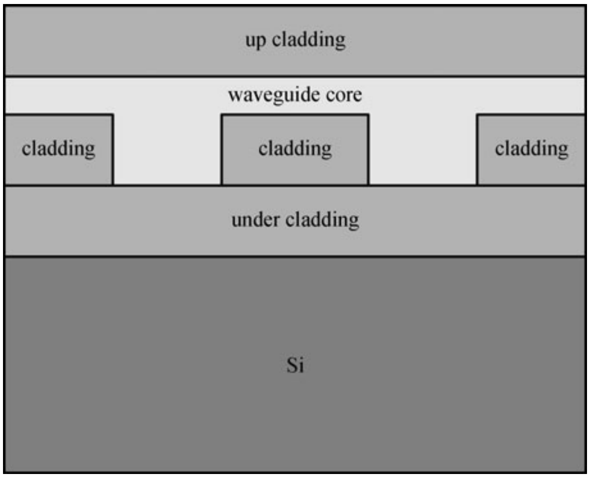

Fig. 8 Inverted ridge waveguide

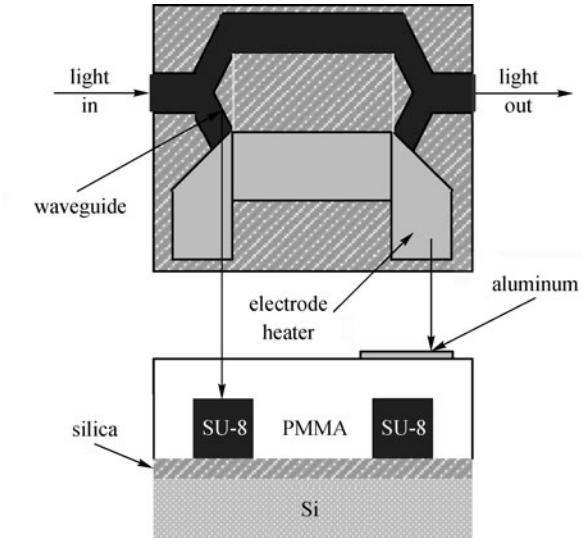

Fig. 9 Structure of MZI-TO switch

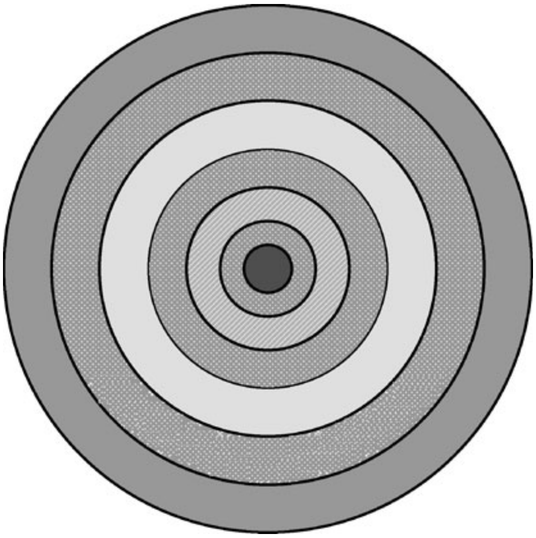

Fig. 10 Schematic diagram of multi-clad-fiber

Heating the micro-electrode can alter the propagation constant for waveguide; an effective interfere or coupling structure will contribute to the alteration in phase of light signal turns into the power of output light [19,20].

In addition, the multilayer ridge waveguide can be used in direct current (DC)-MZI optical switch which has been demonstrated in Ref. [20]; symmetric five-layer planar waveguide, of which the distribution of refractive index looks like ‘W’, can be made into optical switch [21].

In practical application, we can use some basic switch unit, such as 1 × 2 optical switch or 2 × 2 optical switch, to make matrix switch we need.

3.5 Special fibers [22]

Optical fiber is one of the most important and familiar optical waveguide, it is generally called fiber. Special fibers have different functions and performances for different applications. There are many kinds of fiber, such as common single mode fiber, multi-clad-fiber, and so on. The multi-clad-fiber has a very flexible structure on refractive index. And it performs better in dispersion compensation, dispersion flattened, reduction of bending loss and augmentation of mode range by design different refractive index structures.

Figure 10 is the schematic diagram of multi-clad-fiber and Fig. 11 shows the distribution of refractive index.

As Fig. 11 shows, there is different refractive index in each layer because of different kinds of materials shown in Fig. 10. The multi-clad-fiber has an advantage of controlling chromatic dispersion. We can make up the dispersion flattened fiber by adjusting the value of chromatic dispersion. This fiber has little of chromatic dispersion (nonzero) and is even flat in a certain frequency band. The multi-clad compensated fiber can change the waveguide dispersion by altering the total number of cladding, the radius and the refractive index of per cladding. The multi-clad structure brings negative dispersion, and then superimposes the positive dispersion of common fiber to reduce chromatic dispersion value. Finally, the performance of optical communication system is improved.

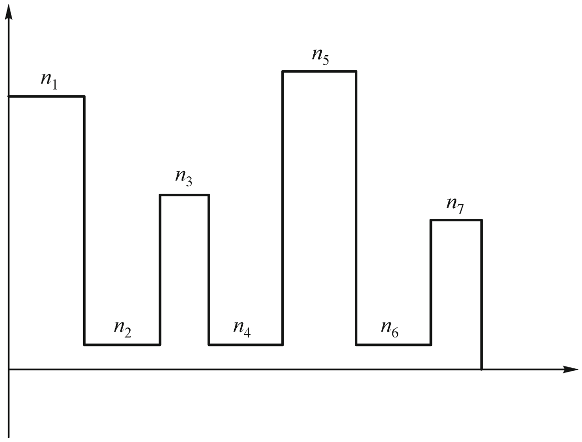

Fig. 11 Distribution of refractive index

The structure of five-clad fiber is presented to make compensated fiber [23]. The core of fiber has a higher refractive index than those of two sink ranges, resulting more negative waveguide dispersion. Having taken the full vector and numerical value measures to analyze the double-clad fiber with left-handed materials in the inner clad, it is found that there are many unusual properties in this five-clad fiber compared with common fiber, and it is considered that these properties are conducive to make late compensated fiber and other optical devices [24]. The multi-clad fiber with metal glass can be used as sensor fiber [25] and the cladding mode resonance of DCF can also be used in sensor [26,27].

4 Comparison

All above optical devices have the structure of multilayer optical waveguide. The work principles of these optical devices are similar. These devices can be made of polymer material or silicon substrate. And these devices have the similar multilayer structures, which are interchangeable.

Both of optical modulator and switch are based on EO effect, AO effect or other physical effects. For optical switch, its ultimate goal is to realize optical switch by changing the amplitude of light; for optical modulator, we modulate the source signal on light signal and transmit it. Both of them can be made by MZI on the multilayer waveguide or combined with optical grating. The optical switch can be cascaded, but the optical modulator cannot.

The laser and the optical amplifier have the same principle. The difference between them is that signal light takes part in the process of amplification in the optical amplifier, while there is only the pump light in the laser. Both the laser and amplifier can be made by DCF or multilayer planar waveguide. And even they have the same structure, sometimes.

The multi-cladding special fiber is the most basic element. It is used not only in dispersion compensation, but also for fabricating laser, optical amplifier, and optical modulator, etc. Multi-cladding fiber grating [28] has wide application in optical devices in the modern time for self merits.

5 Conclusions

In this paper, we reviewed the principle and structure of optical devices based on multilayer waveguide to introduce the basic application of multilayer optical waveguide. The multilayer optical waveguide can be made into adjustable attenuator besides all above devices. For the advantages of itself, such as relatively perfect theories, the ease of changing refractive index and the decreasing of the device loss, multilayer waveguide become more and more important in real application as well as experimental research. Manufacturing new multilayer waveguide device is significant for optical communication in the future.

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