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In-line fiber-optic biconical taper polarizer

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The construction of the in-line fiber-optic polarizer is presented. This element based on the biconical taper structure is positioned on a metal layer. The four-layer planar structure has been used for theoretical investigation of polarizer action. The theoretical results obtained have been compared with experimental investigation of manufactured elements. The technological set-up for the polarizer preparation is also shown. The polarizers have been made for 0.633 and 1.300 μm wavelengths. The first of them has a typical extinction ratio of 25 dB with an attenuation of guided mode of 3 dB. The second one has typical extinction ratio of 30 dB or more, with an attenuation of the desired polarisation of about 2 dB.

1. Introduction

Interferometric fiber sensors utilising standard single-mode fibers are strongly affected by the presence of two polarisation modes in the fiber as they can cause signal fading. Also, in the gyroscopes the selection of a single polarisation at some point along the fiber is required to avoid nonreciprocal phase errors [1]. In an attempt to meet this goal several approaches have been investigated, including the development of polarisation maintaining (PM) and single polarisation (SP) fibers as well as a large number of invasive fiber polarizers.

Invasive devices require access to the evanescent field of the guided mode to induce preferential attenuation of one of the polarisation components. The first reported polarizer of this nature was based on the principle of metal-clad planar waveguides in which the light signal is coupled to the electric current it induces in the metal and suffers a propagation loss *via* ohm losses [2]. With an evaporated CaF_2 film as a buffer layer and a thin aluminium overlay, an extinction ratio in excess of 45 dB and TE_0 attenuation of 1 dB were demonstrated at 0.85 μm [3].

High performance fiber polarizers have been made by placing a birefringent crystal on a polished fiber substrate [4]. The interaction occurred between the evanescent field of the guided mode and the new birefringent cladding. This principle was first put into practice with a crystal of potassium pentaborate which yielded extinction ratios in excess of 60 dB (the best figure that could be measured using conventional techniques) and insertion loss of a few per cent.

A last type of invasive device is the cut-off polarizer [2], [5]. It involves a fiber substrate polished into the fiber core such that both polarisation modes are below cut-off. A thin metal film deposited on the polished surface acts as a bridge for the

TM_0 mode, which is first converted into a plasmon wave at the input of the interaction region and then converted back to the TM_0 wave at the end of the interaction region. With a 5 nm silver or gold film and a liquid buffer layer, a TM_0 insertion loss of 1 dB and an extinction ratio of 47 dB were reported [5].

In this paper, a new concept of polarizer, using a biconical tapered fiber, is described [6]. This device has been made on the basis of a modified metal-clad technique. The main advantage of the technique is an absence of polishing process, which is basal for all the fiber polarizers described above. Starting from the theory of polarizer, through description of manufacturing process and element design, up to extinction ratio and insertion loss measurement are presented, too.

2. Theory of biconical taper polarizer

The main element of the polarizer presented is a biconical taper, made on a single-mode fiber (Fig. 1**a**). It has been found that because of the tapering process, the diameter of the fiber core has been reduced to such an extent that the field distribution of the light has spread out well into the cladding region of the fiber. Then the light becomes guided by the boundary defined by the fiber cladding and surrounding air rather than by the fiber core [7]. Interaction with the guided mode is then achieved by a contact of a metal layer with a fiber taper. In such a way, the anisotropic waveguide covered by metal with a buffer layer (Fig. 1**b**) is obtained. This

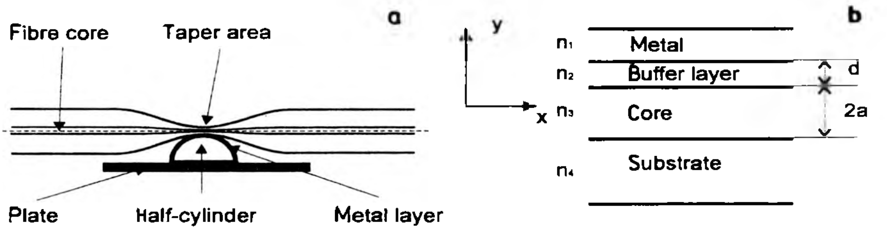

Fig. 1. Polarizer with a metallic cover. **a** — scheme of polarizer structure, **b** — four-layer metal cladding planar waveguide with a dielectric buffer layer — theoretical model of the polarizer.

structure can be a polarizer due to the difference between attenuation of the mode of electric field vector parallel to the metal surface (pseudo-TE_0-mode) and the mode of electric field vector (pseudo-TM_0-mode) perpendicular to its [8].

The above difference is also the base for the determination of a polarizer extinction ratio, defined as [9]

$$\varepsilon = \varkappa_{TM} - \varkappa_{TE} \tag{1}$$

where $\varkappa_{TM}$, $\varkappa_{TE}$ are absorption constants for the corresponding modes of the structure. To determine these parameters the characteristic equation for propagation constant $k_z = \beta - j\alpha$ of the four-layer waveguides has to be solved with complex coefficients in the form [7]

$$2aU_3 = \tan^{-1}\left(\frac{U_4}{-jU_3}\right) + \tan^{-1}\left[\frac{U_2}{U_3}\tan\left\{\tan^{-1}\left(\frac{U_1}{-jU_2}\right) - U_2 d\right\}\right], \tag{2}$$

$$U_l = \sqrt{k_0^2 n_l^2 - (\beta - j\alpha)^2}, \quad l = 1-4, \tag{3}$$

where $2a$ is the thickness of a core layer (taper diameter), d is the thickness of a buffer layer, β is the phase constant, α is the attenuation coefficient, coefficient k_0 is the propagation constant in vacuum.

This equation can be solved only numerically [8]. The parameters in these calculations are the values of refractive indices of waveguide layers (from n_1 to n_4), the type of a cover, the buffer layer width d, the taper thickness $2a$ and the polarizer length L. In these calculations attenuation coefficient α for each mode and the extinction ratio ε related to α by the formula

$$\varkappa = 10(\log e^{2\alpha})L \tag{4}$$

and Eq. (1) are determined for the given polarizer.

In Figure 2, the results of calculations of the extinction ratio ε and the polarizer loss α as a function of taper thickness for two types of metallic covers, namely, aluminium and gold, are shown. In the calculations the following parameters were assumed: the light wavelength $\lambda = 1.3$ µm, the polarizer length $L = 5$ mm and the buffer layer thickness $d = 0.05$ µm. Moreover, it was assumed that the buffer layer as well as the substrate is air with refractive index coefficients $n_2 = n_4 = 1.0$ and the core refractive index is equal to the refractive index of a single-mode optical fiber cladding.

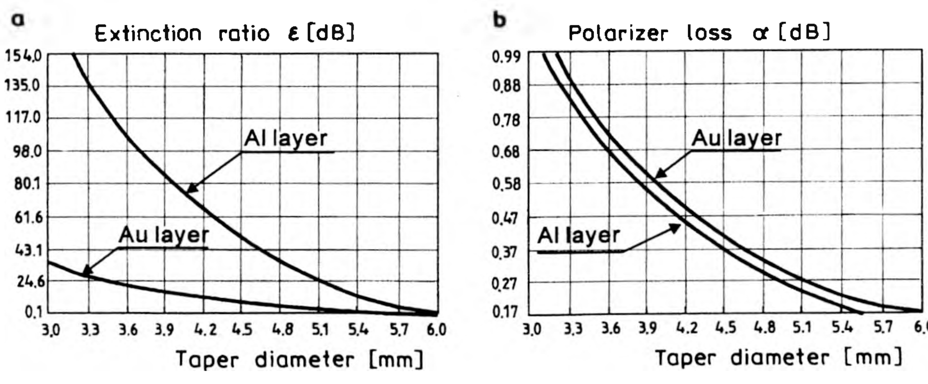

Fig. 2. Theoretical results of extinction ratio (**a**), and loss (**b**) of fiber optic polarizer made of the tapered fiber.

As one can see from Figure 2, the aluminium covered polarizer has better properties than covered by gold. For this device theoretical value of extinction of the order of 130 dB (associated with losses limited to 0.8 dB) can be achieved, but the tapered fiber length should be about 3.3 µm. The necessity to make a big taper may be a technical problem, especially for visible range of light, where single-mode regime of fiber-optic action requires core diameter less than 6 µm.

3. Fiber-optic polarizer manufacturing and design

A technological set-up for preparing fiber polarizer, shown in Figure 3, has been built. This device enables us to control all parameters during the process of tapering the fiber as well as final polarizer manufacturing. In this apparatus, the fiber was properly heated using a propane-oxygen flame, then the fiber was being stretched to

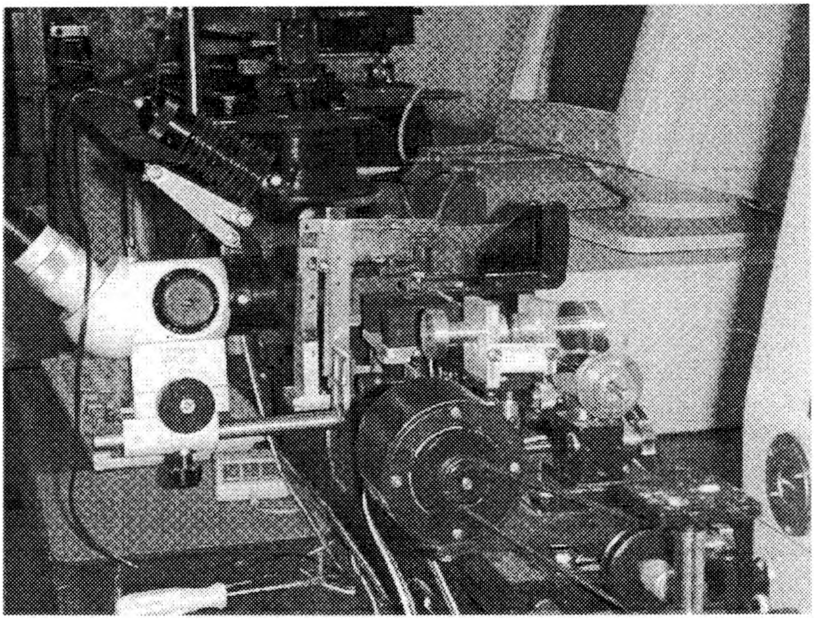

Fig. 3. General view of the set-up for polarizer manufacturing.

obtain tapering and simultaneously the light introduced at one end of the fiber was measured at the other end. The process was carried out by keeping the output level of light almost constant. The requirement is to get the properly tapered fiber, without introducing insertion loss to the measured tranmission through the fiber. The last step of polarizer preparation was to make the one-side contact of the fiber with the metal layer. In this step, a plate supporting the half-cylinder rod with a metal layer deposited on it has been shifted towards the fiber taper. At this moment the polarizer quality has been tested by the emasurement system shown in Fig. 4. The minimum I_{min} and the maximum I_{max} intensity for different input states of polarisation (SOP) has been measured on the detector D. The polarisation controller PC placed in-line before the polarizer has been used to obtain different SOP.

From the measured values I_{max} and I_{min}, the polarizer extinction ratio has been expressed in dB as [11]

$$\alpha = 10\ \log(I_{max}/I_{min}). \tag{5}$$

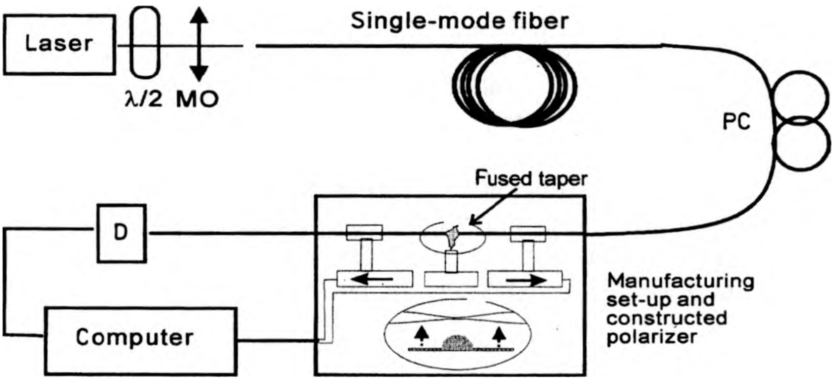

Fig. 4. Scheme of the system for monitoring taper process as well as measuring polarizer properties. MO – microscope objective, PC – polarisation controller, D – detector, $\lambda/2$ – rotated half-wave plate ⟶ and ⟵ step motors tapering the fiber.

In the end, the polarizer attenuation loss, defined as a decibel ratio of the output light intensity I_{out} to the input one I_{in}, has been measured by classical cut-off method as [11]

$$\alpha = 10 \log(I_{in}/I_{out}). \tag{6}$$

The final construction of the polarizer is shown in Figure 5. A tapered fiber is attached to a quartz plate supporting the half cylinder rod with Al-metal layer deposited on it. The tapered fiber touches this metal layer [6]. The fiber/substrate structure is placed into a metallic tube for general protection. Rubber boots are on the ends to seal the device and provide strain relief to the fiber as they exit the polarizer.

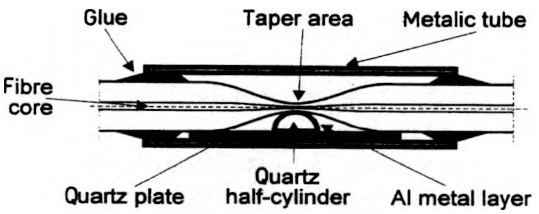

Fig. 5. Schematic view of fiber-optic polarizer.

4. Measurements of polarizer parameters

The standard optical system containing a source, a quarter-wave plate, the Glan-Thompson bulk polarizer, the measured polarizer, and a detector has been used for polarizer testing. The input system, in front of the measured fiber-optic polarizer, ensures injection of the linear SOP with any azimuth. The measurement of the output intensity from the fiber polarizer for changing input azimuth of SOP in the range of 360 deg, allows us to obtain the extinction ratio as well as the loss [11].

The main disadvantages of the above method are problems with justifying the system, especially in infrared, and limitation of the measured extinction ratio to the extinction value of the bulk polarizer applied. The use of fiber-optic loop interferometer, in classical gyro configuration, gives a possibility to measure the extinction ratio of any value [12]. Because in this system the drift value is closely connected with extinction ratio of the fiber polarizer, then measurement of a drift can be used for estimation of the extinction ratio. The parameters of polarizers manufactured in the Applied Physics Department (Institute of Applied Physics – Military University of Technology, Warszawa, Poland) are shown in the Table.

Table. Main parameters of manufactured fiber-optic polarizers

Wavelength λ [nm]	Optical fiber type	Extinction ratio ε [dB]	Attenuation loss α [dB]	Kind of measurement
633	UMCS, Lublin	~25.0σ2.5	3.00	Classical
830	UMCS, Lublin	~23.0σ3.2	2.50	Classical
1300	ITI	~40.0σ5.0	2.00	Classical
	Iskra-CEO	32.22σ0.82	2.20	Fiber Gyro
		36.98σ0.81	2.00	
		32.98σ0.95	1.60	

As one can see from the above, in practice, the fiber-optic polarizers have worse parameters than calculated theoretically (*i.e.*, for constructional parameters as reported in comment to Fig. 2, the extinction over 40 dB with the loss below 2 dB). The main source of this problem is connected with good preparation of metal layer (especially its cleanness, homogeneity and smoothness).

5. Summary and conclusions

A new type of fiber optical polarizer that uses a tapered fiber is described. The advantage of the presented device is simplicity of its manufacture. All processes can be performed without removing fiber from the set-up. The manufacturing process enables preparation of fiber-optic polarizer for any wavelength needed. The obtained polarizer parameters depend on wavelength – the larger wavelength guarantees better parameters mainly due to larger diameter of a single-mode fiber core. The best fiber polarizer obtained so far at the operating wavelength of 1.3 μm had the extinction ratio 36.98σ0.81 dB and the attenuation loss of about 2 dB which was little higher than in commercially available comparable devices. The polarizer presented was successfully used to build a gyroscope and some other fiber sensors.

The set-up used for polarizer manufacturing has an additional possibility of fiber-optic coupler making. The technology of this device is based on the same biconical fiber tapering structure. In the future we intend to manufacture polarisation maintaining couplers on the basis of the above set-up.

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