Concept of Optical Sensor Utilising the Far Field Pattern Radiated by Periodic Grating Strips Over Silica Cladding on the Silicon Wire Waveguide

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***Abstract*—This paper describes the novel concept of the optical sensor, which utilizes the physical nature of the light propagating in a silicon wire with the periodic segmented grating placed in the waveguide vicinity over the silica buffer. In specific cases, this segmented grating works as a virtual leaky waveguide, which radiates power as an outcoming optical beam having small both wavelength band and beam divergence. The radiation angle strongly depends on the refractive index of the grating environment. Thus, this device can be used as an optical sensor with the readout to be arranged by measuring the far field pattern in the focal plate of the lens, which is placed near the sensor element. The device concept is verified by direct numerical modelling through the Finite Difference Time Domain (FDTD) method.**

Keywords-silicon wire; segmented grating; far field patern; optical sensor; numerical modeling; FDTD method.

I. INTRODUCTION

The most popular optical sensors are based on the high precision measuring the optical wavelength that propagates in the photonic structure and whose properties depend on the environment of the sensor element. It can be done by a tunable laser with a fine linewidth or by launching into the waveguide the optical beam, which contains a broad wavelength range, say, from the super-luminescence diode, and measuring the transmitting signal by the Optical Spectrum Analyzer (OSA). Both these variants provide the possibility to develop advanced optical sensors with the sensitivity depending on the design of optical element and the spectrum resolution of the tunable laser or the OSA. Both of these readout schemes are rather costly, which prevents the wide spread of these sensor technologies.

The current paper presents the new concept of the optical sensor design. The idea of this sensor comes from the background of optical phenomena, which takes place in the silicon wire with the periodic segmented grating evanescently coupled through the silica buffer.

When the guided optical beam, which contains a broad spectral range, arrives in the grating area (see Figure 1), different optical processes can occur, depending on the ratio between the optical wavelength λ_0 and the grating period Λ [1]. In this paper, we will not discuss the well-known effect of the Bragg reflection to the guided wave propagating in a silicon wire in the opposite direction and the broadband interaction with radiation modes that provides the outcoming optical wave with the radiation angle depending on the optical wavelength. Our investigation is focused on the resonance-type interaction of incoming guided wave with the virtual leaky wave that is supported by the periodic grating structure, coupled by the evanescent field with the underplayed silicon wire. We call this type of diffraction regime "abnormal blocking" [2]. It is interested to note that this interaction is a resonance type, like a Bragg reflection, and it is supported by the outcoming optical beam, like a coupling with the radiated modes. However, in contrast to the last process, the coupling to radiated modes has a resonance feature and thus this effect of "abnormal blocking" can be used for sensing applications [2].

The paper is structured as follows. In Section II we define the sensor design and features, while in Section III we summarize the conclusions.

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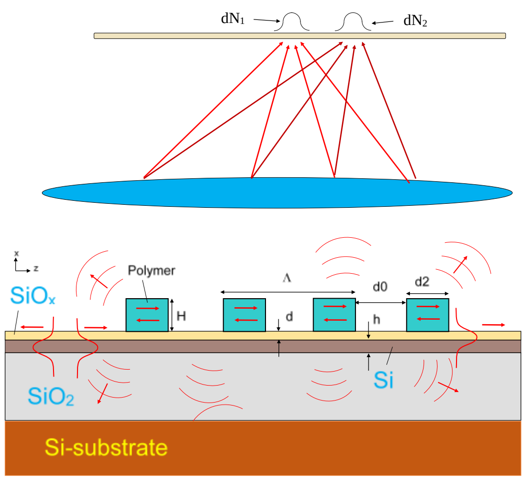

Figure 1. The principal design of optical sensor based on the interaction of the guided wave with the virtual leaky wave of the segmented grating. Here, Λ = d0 + d2 is the period of grating, H and d2 are the height and the width of the segmented grating, d0 is the spacing between the strips, d and h are the waveguide and buffer heights, respectively.

II. SENSOR DESIGN AND FEATURES

The principle of this type of sensor is based on the utilization of the radiated feature of coupling the guided to the virtual leaky wave, which takes place in the segmented grating structure placed in the vicinity of the silicon wire waveguide. This interaction has the maximum effect when the well-known Bragg condition on conservation of the momentum is satisfied:

$$N_L = \pm N_g - p\cdot\lambda/\Lambda = n_0\cdot\sin(\varphi) \qquad (1)$$

where N_L and N_g are effective indices of the leaky and guided waves of the silicon waveguide with the segmented grating structure, p is the diffraction order of the grating, φ and n_0 are the radiated angle (relative to the structure normal) and the refractive index of the grating environment, say, the water for the case of a liquid sensor, respectively.

The changing of the grating environment index by the amount dN leads to the change in the condition (1) of diffraction observation. This change is the subject of the measurement by the optical sensor. The main sensor parameters could be derived from Eq. (1) in the form of the following set of equations:

$$\partial N_L/\partial n = \pm\,\partial N_g/\partial n - \partial\lambda/\partial n\cdot p/\Lambda \qquad (2)$$

$$S_n = \partial\lambda/\partial n = \Lambda/p\cdot(\partial N_L/\partial n \;-/+\; \partial N_g/\partial n) \qquad (3)$$

$$\varphi_n = \partial\varphi/\partial n = -\,p/[\Lambda\; n_0\cdot\cos(\varphi)] \qquad (4)$$

Eq. (2) is characterized by the mode index sensitivity of the sensor. In order to improve the sensitivity, one can use the waveguide near the cutoff, the slot [3][4] or segment waveguide structures [5]. Eq. (3) describes the homogeneous sensitivity of the typical sensor, which works by measuring the Drop wavelength of the structure. The last Eq. (4) corresponds to the homogeneous sensitivity feature of our sensor, which measures the small index variation by the determination of the diffraction angle of the radiated power, which is generated during the interaction of guided and virtual leaky waves. This effect of “abnormal blocking” [2] has a resonance feature and thus this radiated angle φ has also the resonance behavior on the optical wavelength. By the analysis of the far field diffraction, corresponding to the condition of realization of the “abnormal blocking”, one can get information about the index change in the grating vicinity. This analysis can be done by using the field distribution in the focal plate of the lens obtained by the charge-coupled device (CCD) camera.

The structure design, which is under investigation, is shown in Figure 1. The silicon wire having the height h = 250 nm and the width w = 450 nm is placed on a thick 2 μm silicon dioxide buffer. It corresponds to the optical waveguide, which supports a transverse electric (TE)-polarized single mode (electric field in the plane of the waveguide). The segmented structure is achieved by the periodic (Λ = 1.3 μm) strips from polymer SU-8 (index n_p=1.56) with length 0.50 μm, height H = 1.0 μm and width W=1.0 μm and which is separated from the silicon waveguide by a silica overlayer from a flowable oxide (FOx) having height d = 200 nm and index 1.4.

This structure is investigated by numerical modeling, which has been performed using the Finite Difference Time Domain (FDTD) method through the commercial software package RSoft-SYNOPSYS [6]. In order to examine the long structure, we utilize FDTD under the two dimensional (2D) approximation based on the effective index method (EIM) [7], as in Figure 2. Previously, we have shown that the EIM method has a fundamental limitation [8][9], which takes place when trying to analyze the pulsed excitation of waveguide structures by 2D FDTD method.

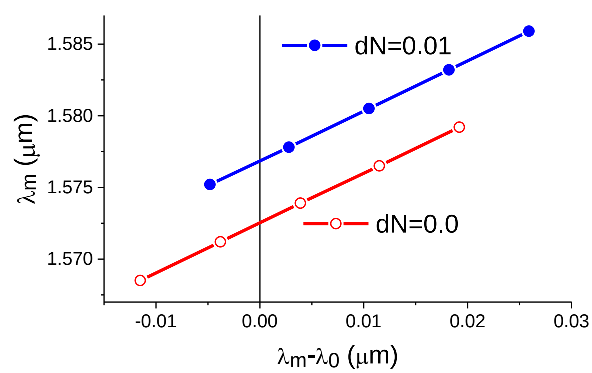

Figure 2. The algorithm for the dispersion compensation for two-dimensional simulation by FDTD method using EIM.

The reason is that the two-dimensional EIM approximation does not take into account the waveguide dispersion, which is the fundamental feature in the propagation of a short pulse containing a wide spectral composition. Therefore, the classical EIM can be used only for the monochromatic excitation of a waveguide.

We found an original solution to this problem. The presence of waveguide dispersion leads to the fact that the wavelengths of anomalous blocking λ_m found using the 2D FDTD modeling depend on the wavelength λ_0, at which the impulse excitation and spectrum analysis of the waveguide structure is carried out. However, for the case when $\lambda_m = \lambda_0$ this value is exactly equal to the desired value. Therefore, by constructing the dependence λ_0 on the difference λ_0-λ_m and having determined the values λ_0 at the zero coordinate (see Figure 2), it is possible to find the wavelengths of the anomalous blocking for different values of the perturbation of the refractive index of the environment. This optical wavelength (determined for different values of the environment indices and structure parameters) is used for all simulations. This algorithm allows to determine the correct values S_n and φ_n, by 2D FDTD plus EIM.

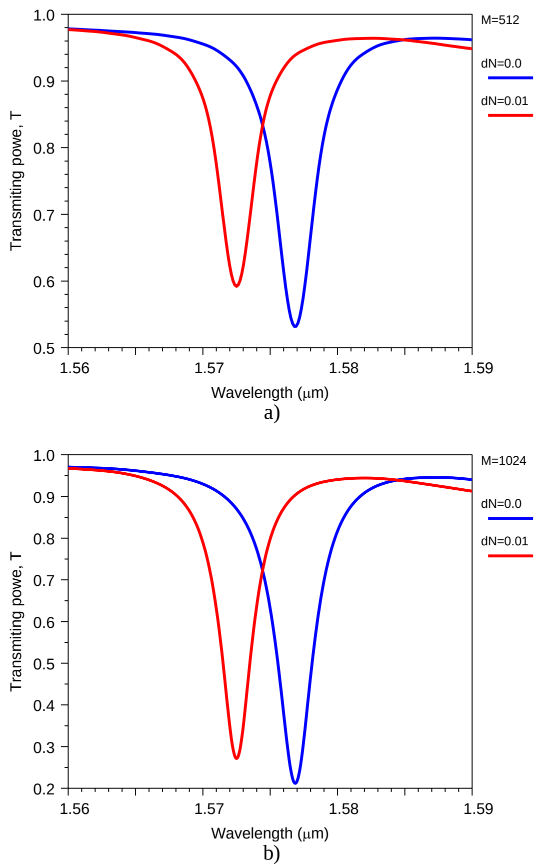

Figure 3. Transmitting power (T) relative to the input signal of the guided wave, which propagates along the silicon wire with segmented grating: a) M=512, b) M=1024.

The sensor element, based on segmented grating over the silicon waveguide, can be used through different readout schemes. The traditional variant based on measuring the transmitted spectrum is illustrated in Figure 3 for different number of segments M=512 and M=1024. One can see that the suppression of the Drop wavelength is increased with increasing the grating length ($\Lambda \times M$), but this does not increase the filter resolution (half width 3.3 nm), which is restricted by the optical decay of the leaky wave supported by the grating. Nevertheless, by measuring the optical wavelength, one can determine the index variation. For the case of water environment, we have the homogeneous sensitivity $Sn=\partial\lambda/\partial n$ = 440 nm/RIU. For the case of an Optical Spectrum Analyzer (OSA) resolution of 0.01 nm, it provides the sensor resolution of 1.3 10^{-5} RIU.

Similar sensitivity can be achieved by measuring the far field distribution of the optical wave, radiated by the grating structure, in regime of “abnormal blocking” effect. In order to prove this statement, we plot in Figure 4 the angle variation of the far field pattern of radiated power, corresponding to the 20 different wavelengths around the drop wavelength of “abnormal blocking”. These far field patterns produce the index-dependent variations in the power distribution in the focal plate of the lens (see Figure 5), which could be measured by the matrix photodetector.

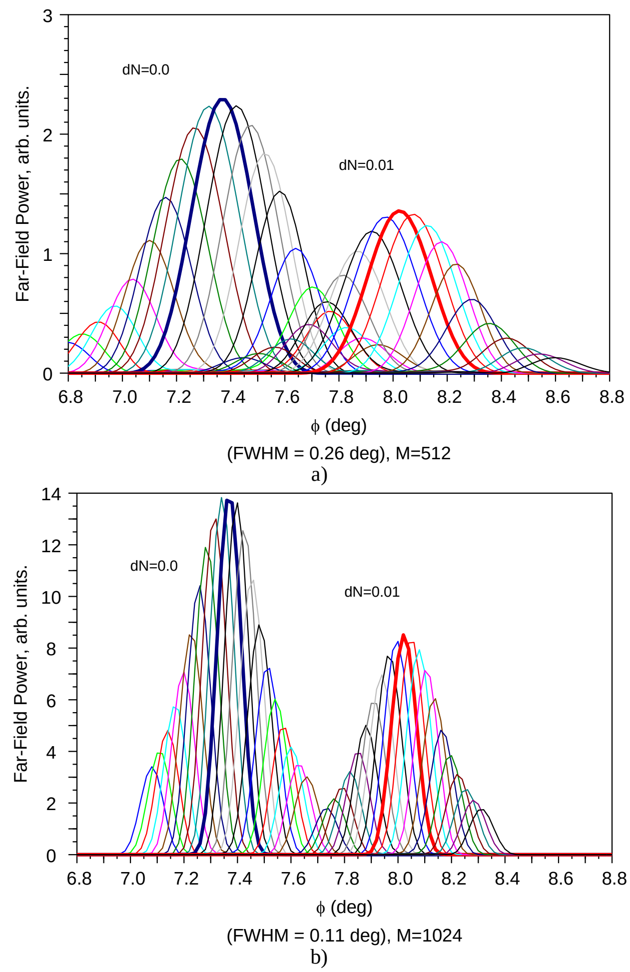

Figure 4. The angular variation of the far field pattern. It is produced by the guided wave, which propagates along the silicon wire with segmented grating: a) M=512; b) M=1024.

The thick lines in Figure 4 correspond to the far field of the monochromatic wave incidence at drop wavelengths 1.5768 μm and 1.5725 μm for dN=0.0 and dN=0.01, respectively.

The structure has a limited bandwidth (3.3 nm) of wavelength response (see Figure 3). Thus, the part of the optical wave at different wavelengths (around the drop one) will be also scattered by the grating and will propagate at different angles (see (4)). These additional far field patterns are shown as thin lines in Figure 4 and Figure 5. They also increase the beam divergence relative to monochromatic wave. Our analysis proves that this device is suitable for measuring the small variation of the refractive index of the grating environment. Besides, the sensor resolution is increased with increasing the number of segments in the grating. For 1024 segments, the angle deviation for dN=0.01 is twice the optical beam divergence.

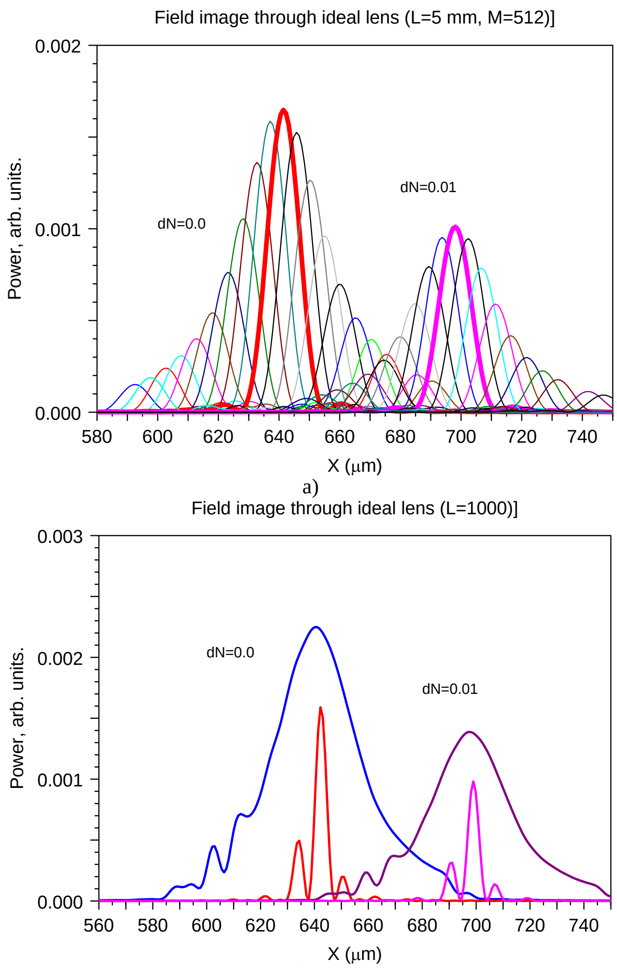

Figure 5. The power distribution in the focal plate of the ideal lens having the focal length 5 mm for the case of M=512 and different index variations dN=0.0 and dN=0.01 of the environment (water): a) a set of far field patterns corresponding to different optical wavelengths around the Drop one; b) the total power distribution (as a sum of 20 different wavelengths), which has to be measured by the photodector array.

It means that under the same condition (the ratio of the Drop resolution to the pattern half width) the proposed sensor will provide 1.5 better resolution than in the OSA readout of the same device, with an arrangement for measuring the far field pattern much simpler and cheaper.

III. CONCLUSION

We have proposed and carried out numerical modelling of a novel type of optical sensor, which utilizes a segmented periodic structure over the silicon wire. The tunnel coupling of the guided wave to the segmented structure provides excitation of the virtual leaky wave in the periodic segmented structure. The last radiates the power as an outgoing optical beam. This process has a resonance nature and takes place at small wavelength range (around 3.3 nm), thus the outgoing optical beam has a small divergence (0.33 degree), which makes possible to determine small index environmental variations by measuring the change in the far field pattern distribution. This can be accomplished by commercial CCD arrays placed in the focal plate of the lens in an optical solution much simpler and cheaper than a tunable laser or an OSA.

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