Miniature Otto configuration implemented by two-photon laser lithography

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Abstract. In this work we develop the concept of miniature Otto configuration. The distinctive feature of the proposed prism configuration is an operation for normal angle of incidence. Polymer microprisms with size of several tens of microns were fabricated by two-photon laser lithography on a surface of one-dimensional photonic crystal. The performance of the prisms was studied in the case of the Bloch surface waves excitation. Design of the prism and its optimal geometrical parameters were obtained from results of calculations. Bloch surface waves excitation with the microprisms was observed by the leakage radiation microscopy. The dependence of coupling efficiency on the angle of incidence was studied. Proposed prism configuration is easily compatible with fibers and is very appealing alternative to diffraction grating coupling for future applications.

1. Introduction
Recent years have been marked by the active development of such an area as photonics[1]. Great progress has been made in the field of both all-dielectric and plasmonics photonics platforms[2]. However, regardless of the material, researchers always face the same problem: the need to couple free-space or fiber radiation to photonic devices. The problem is of particular importance for waveguides. This task could be solved by providing either wave-vector matching or large overlap between excitation beam and desired mode. Wave-vector matching is realized by prism or grating coupling while large overlap is obtained by end-fire coupling. End-fire method is especially popular for fiber coupling and provide high efficiency. Disadvantages of this method are requirements of precise alignment and facet polishing which is not always possible. Grating is a standard solution for SOI platform and could potentially provide unidirectionality and high efficiency[3]. However, these properties are achieved with complex design or with coupling the excitation beam at an angle to the grating. Prism coupling, in turn, theoretically provides high efficiency[4], but is rarely used due to large dimensions and requirement for angle of incidence other than normal. In our work we propose microprism that implements Otto configuration without aforementioned limitations. For this purpose the two-photon laser lithography is used that was shown to be compatible with fibers[5] and to be excellent tool for hybrid photonic integration[6].
The performance of the miniature Otto configuration is studied using so-called Bloch surface waves (BSW). BSW are surface electromagnetic waves on the interface between one-dimensional photonic crystal (PC) and dielectric[7]. BSW represent an all-dielectric counterpart to well-known surface plasmon polaritons. BSW have longer propagation length and are not limited to one polarization and can be both TE- or TM-polarized. BSW frequency and wave vector could be tuned to any desired value with careful designing of PC layers materials and thicknesses.

In this work we demonstrate polymer microprisms on the surface of one-dimensional PC. Microprism’s size ($H \times W \times L$) is about $24 \times 30 \times 24 \, \mu m^3$. These prisms implement miniature Otto configuration and are utilized to excite BSW at $\lambda = 780$ nm. The BSW excitation is studied by the leakage radiation microscopy (LRM)[8].

2. Results and discussion

2.1. Samples

Our samples based on 1D PC, which was designed to sustain TE-polarized BSW at $\lambda = 780$ nm. PC consisted of 10 pair of alternating SiO$_2$ ($n_{SiO_2} = 1.45$) and Ta$_2$O$_5$ ($n_{Ta_2O_5} = 2.07$) layers sputtered on 170 µm glass substrate. The thicknesses of SiO$_2$ and Ta$_2$O$_5$ layers were 204 nm and 143 nm, respectively. The terminating layer of photonic crystal was SiO$_2$, which enabled BSW excitation on the bare PC. BSW was described by dimensionless parameter called effective refractive index $n_{eff}$ which is equal to ratio of BSW wave vector to the vacuum wave vector at the same frequency. For our PC the BSW effective refractive index $n_{eff} = 1.092$ was calculated at $\lambda = 780$ nm by the transfer matrix method.

Microprisms were fabricated on the PC surface by custom two-photon laser lithography setup[9]. Radiation from laser source (Ti:Sa femtosecond laser, 800 nm, 80 MHz repetition rate) was focused by an oil-immersion objective (NA= 1.4, 100X) mounted on a piezo stage. Fast steering mirror provided rapid beam movement in the lateral directions. Hybrid organic-inorganic photoresist SZ2080 was used in the lithography process. A droplet of SZ2080 was placed on the PC surface. Laser radiation was focused through PC and microspisms were fabricated starting from the facet far from the PC surface.

2.2. Micro prism

Microprisms were designed to implement Otto configuration at normal angle of incidence. A special prism model was developed for this purpose (longitudinal cross-section is shown in Fig. 1a). Radiation fallen on the upper surface and transmitted into the prism underwent total internal reflection on a slanted facet. After that the radiation reached a gap region where frustrated total internal reflection took place just like in conventional Otto configuration. For an optimal performance 4 parameters (slope angle $\alpha$, gap height $d$, gap length $L$ and prism height $h$) should be determined.

In conventional Otto configuration the angle of incidence on the prism base $\varphi$ should provide wave-vector matching. In terms of effective refractive index this condition can be written as $n_{prism} \sin(\varphi) = n_{eff}$. In our case the prism refractive index $n_{prism}$ was equal to SZ2080 refractive index $n_{SZ2080} = 1.5$. Angle $\varphi$ depended on angle $\alpha$ and angle of incidence on the slanted facet $\beta$. In case of normal incidence on the upper facet of the prism $\beta = \pi/2 - \alpha$. Thus the angle of incidence $\varphi$ was equal to $2\alpha$. The wave-vector matching condition led to $\alpha = 23.3^\circ$. The prism height $h$ must be large enough so that the spot with diameter $2r$ completely falls on the slanted facet. Thus $h \geq 2r \cotg(\alpha)$. We limited beam size to 10 µm therefore $h = 23.2 \, \mu m$. Two remaining parameters were determined as a result of numerical 2D calculation which was performed by the Lumerical FDTD.
2.3. Calculations

In 2D FDTD simulation the prism was modeled as a trapezium above the PC surface. SiO$_2$ and Ta$_2$O$_5$ layers were modeled as dielectrics with refractive indices and thicknesses equal to experimental ones. The Gaussian source was used in simulation. It was located at a distance of 2 µm from the prism upper facet and centered relatively to the slanted facet. Beam waist was set to 10 µm. The simulation volume was enclosed by Perfectly Matched Layers (PML). The amount of energy propagating in the PC far from a prism (on a distance of 10 µm) served as an indicator of coupling efficiency.

First of all, optimal angle $\alpha$ was estimated. The dependence of coupling efficiency on $\alpha$ was obtained for this purpose. The angle $\alpha$ value calculated by FDTD was in agreement with the value evaluated by the transfer matrix method. Then we simultaneously optimized $L$ and $d$. Obtained values were 14 µm and 290 nm, respectively. These numbers set a realistic goal for the prism fabrication by the two-photon laser lithography. A set of microprisms with estimated parameters was fabricated (Fig. 1b). The gap height $d$ varied from 200 nm to 600 nm. Transverse gap size was set to 5 µm while full prism transverse size was 25 µm (Fig. 1c).

2.4. Leakage radiation microscopy

The excitation of the BSW with microprisms was studied by the LRM which made it possible to investigate near-field distribution with the radiation detected in the far field. Radiation from a diode laser ($\lambda = 780$ nm) was focused by an air objective (NA=0.25, 10X). However, laser beam size was equal to 1.8 mm which was smaller than objective pupil diameter. Thus the objective provided reduced numerical aperture of 0.05. In this case the focal spot size could be estimated as 10 µm. BSW detection was performed by an oil-immersion objective (NA=1.3,
100X) brought into contact with the glass substrate. The high NA objective collected part of the BSW radiation leak to the substrate. The front and back focal planes of the collecting objective were projected on two CMOS cameras. It enabled us to simultaneously study near-field distribution and wave-vector distribution of the BSW. The intermediate front and back focal plane images were additionally constructed to perform filtering of the obtained images, thus we were able to visualize radiation corresponding only to the excited BSW. An example of the filtered front focal image is shown in Fig. 1e. Typical BSW field distribution is observed. Moreover, BSW $n_{\text{eff}}$ equal to $1.1 \pm 0.01$ was obtained from back focal plane image. This value is in a perfect agreement with the value predicted by the calculations.

After that the dependence of coupling efficiency on the angle of incidence was studied. For this, the laser diode was translated in the plane parallel to the focal plane of the focusing objective, which led to a change in the angle of incidence with the focal spot position unchanged. The numerical aperture of the focusing objective limited the range of available angles of incidence to $[-14^\circ : 14^\circ]$. For each angle of incidence, the integral of BSW intensity on the LRM image was calculated, which allowed us to estimate the coupling efficiency. Maximum efficiency was obtained at an angle of incidence close to normal.

3. Conclusion
In this work we developed the concept of miniature Otto configuration and demonstrated its viability by the example of the Bloch surface waves excitation. Prisms had a size about $24 \times 30 \times 24 \ \mu\text{m}^3$. The optimal parameters of the prism were obtained as a result of calculations. Microprisms were fabricated from polymer SZ2080 by two-photon laser lithography on the surface of one-dimensional photonic crystal. Bloch surface waves excitation with the microprisms was observed by the leakage radiation microscopy. Experimentally obtained Bloch surface waves effective refractive index $n_{\text{eff}} = 1.1 \pm 0.01$ was in close agreement with predicted $n_{\text{eff}} = 1.092$. The dependence of coupling efficiency on the angle of incidence was studied. Designed microprisms possessed performance at normal angle of incidence. Proposed prisms are easily compatible with fibers which is very attractive for future application.

4. Acknowledgments
This work was supported by the Russian Foundation for Basic Research (grant №18-32-00841) and the Russian Science Foundation (grant №15-12-00065).

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