Multimode interference of Bloch surface electromagnetic waves

Safronov K.R.,† Gulkin D.N.,† Antropov I.M.,† Abrashitova K.A.,† Bessonov V.O.,*, †, ‡ and Fedyanin A.A.†

†Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
‡Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow 119071, Russia

E-mail: bessonov@nanolab.phys.msu.ru
Phone: +7 (495) 939-39-10

Abstract

Integrated photonics aims at on-chip controlling light in the micro- and nanoscale ranges utilizing the waveguide circuits, which include such basic elements as splitters, multiplexers, phase shifters. Several photonic platforms, including the well-developed silicon-on-insulator and surface-plasmon polaritons ones, operate well mostly in the IR region. However, operating in the visible region is challenging because of the drawbacks originating from absorption or sophisticated fabrication technology. Recently, a new promising all-dielectric platform based on Bloch surface electromagnetic waves (BSWs) in multilayer structures and functioning in the visible range has emerged finding a lot of applications primarily in sensing. Here we show the effect of multimode interference (MMI) of BSWs making the key step towards implementing the advanced integrated photonic devices on the BSW platform. We determine the main parameters of MMI effect and demonstrate the operation of Mach-Zehnder interferometers with
a predefined phase shift proving the principle of MMI BSW-based photonics in the visible spectrum. Our research paves the way to developing a versatile toolbox of the BSWs platform devices which can be essential in integrated photonics, lab-on-chip, and sensing applications.

**Keywords**

Bloch surface waves, integrated photonics, photonic crystals, multimode interference devices, waveguide couplers, Mach-Zehnder interferometer

**Main text**

Photonic integrated circuits consisting of waveguides, splitters, interferometers, multiplexers, etc., are the key elements for implementing all-optical computing and low-loss data transfer using both classical\(^1\) and quantum\(^2\) light. The common approach of implementing the waveguide regime relies on creating a refractive index contrast when the light is captured in a medium with a higher refractive index. The waveguide miniaturization requires a high refractive index contrast, so the waveguide core and cladding should be made of different materials that are compatible with each other and capable of being structured. This limits the possible combinations of materials and imposes the need to use sophisticated multi-stage fabrication techniques to develop integrated optical platforms, especially those operating in the visible range.\(^3\) Another approach to on-chip controlling light is to use two-dimensional surface electromagnetic waves (SEW) propagating along an interface between two media. The waveguide regime can be obtained by structuring one of the media, which is widely demonstrated for surface plasmons,\(^4\) and more recently for Tamm plasmons\(^5\) and Dyakonov surface waves.\(^6\) The possibility to apply the low-refractive-index materials,\(^7\) such as polymers, which are easily structured using industrial lithography techniques, makes SEW approach highly promising for integrated photonics. However, the use of metals is always
accompanied by ohmic losses dramatically increasing in the visible range, while the use of anisotropic materials significantly limits the propagation direction of Dyakonov waves. This leads to the quest for alternative photonic platforms that do not suffer from these limitations.

At this moment, a promising all-dielectric 2D photonic platform based on Bloch surface waves (BSWs) is being actively developed. BSWs are surface electromagnetic waves that exist at the interface between a truncated periodic dielectric multilayer (1D photonic crystal (PC)) and an adjacent dielectric medium. BSWs are sustained in the spectral region of the PC photonic stopband and outside the light cone. The frequencies and values of the wavevectors of TM- and TE-polarized BSWs are fully controlled by the structure and parameters of the PC resulting in great freedom in the choice of PCs materials in designing the BSW platform. BSWs were demonstrated in the ultrawide range of excitation frequencies from UV to C-band and mid-IR region. The use of lossless dielectric media guarantees a long propagation length up to several mm and even up to cm in the visible. All these attractive features have inspired various studies aiming at application of BSWs primarily in sensors, as well as for micromanipulation, surface-enhanced Raman scattering, and exciton-polariton excitation. The BSW-induced effects such as giant Goos-Hanchen shift, enhanced magneto-optical and nonlinear optical effects, and enhanced fluorescence emission were also observed. The combination of planar nature, spectral flexibility, large propagation length and field enhancement of up to four orders of magnitude makes BSW platform highly promising for integrated optical technologies.

The first step in developing BSW integrated optic platform is gaining control of BSW propagation. As in the case of other types of surface waves, this can be achieved by simply structuring the top layer of the PC or a thin dielectric layer deposited on top of the PC. This concept is widely used to control BSWs on a bare surface of the PC, particularly to generate, split, and focus BSWs. The BSW waveguide modes were first observed in a thin polymer ridge on the surface of the PC. Subsequently, only a few BSW waveguide configurations were studied, including straight and curved waveguides, disk and
ring resonators.

In this work, we expand the concept of BSW-based integrated photonics and develop an approach to implement the integrated optical splitters and phase shifters using multimode interference (MMI) effect. The operation of MMI devices is based on the self-image principle, which manifests itself in multimode waveguides as periodic reproduction of the input field profile in one or multiple replicas (self-images) due to the interference of a number of waveguide modes. MMI devices are fundamental elements in advanced photonic circuits and are widely applied for on-chip splitting, multiplexing and switching due to their compactness, low losses, large fabrication tolerance and large optical bandwidth. We prove both experimentally and numerically the multimode interference of Bloch surface waves propagating inside polymer multimode waveguides fabricated on top of a one-dimensional photonic crystal. We visualize the MMI patterns using leakage radiation microscopy, study their properties depending on the width of the waveguides, and develop MMI couplers and phase shifters on the BSW platform. Based on the obtained results we have successfully designed and fabricated Mach-Zender interferometers (MZI) with the phase shift of 0 and $\pi$, showing constructive and destructive interference at the output port.

Results

Sample design and experimental technique

The studied system and the experimental idea behind it are illustrated in Fig. 1a. The sample is a one-dimensional PC with polymer waveguide structure on its surface. The most important parameter of the waveguide is its height, which determines the maximum effective refractive index of BSW waveguide modes. The height can vary from tens to hundreds of nanometers depending on the PC parameters. Herein we chose the PC consisting of 5 pairs of SiO$_2$/Ta$_2$O$_5$ quarter-wavelength-thick alternating layers sputtered on a coverslip. The thicknesses of layers are 140 nm (SiO$_2$) and 98 nm (Ta$_2$O$_5$), that correspond to the
Bragg wavelength of $\lambda_B = 810$ nm. The PC topmost layer is $\text{Ta}_2\text{O}_5$ layer with higher refractive index. In this case, the BSWs cannot exist on a bare surface of PC and their excitation requires an additional dielectric layer.\(^9\) Thereby, a 210-nm-thick layer of SU-8 photoresist was spin-coated on top of PC and structured by two-photon laser lithography technique\(^{35}\) to obtain series of coupling and waveguide elements sustaining BSW excitation and propagation. The height of all fabricated elements was governed by the height of SU-8 film and amounted to 210 nm providing the BSW waveguide modes with the maximum value of effective refractive index of $n_{\text{eff}}^{\text{max}} = 1.13$ for TE-polarized excitation radiation with the wavelength of 670 nm. A detailed description of the photonic crystal properties and fabrication of polymer structures are reported in Ref.\(^{35}\) and described in the Materials and Methods Section and in the Supplementary Information, Section S1.

Fig. 1b schematizes the structure designed to study the multimode interference of BSW. The MMI structures consist of a coupling part composed of diffraction grating with a focusing taper and a waveguide part containing an input narrow single-mode waveguide followed by a wide multimode waveguide terminated by an output single-mode waveguide. The fundamental BSW mode propagating in the input single-mode waveguide excites a set of BSW modes in the multimode waveguide. The modes interfere with each other and form a periodic pattern of field distribution (self-images) within the multimode waveguide. The number of interfering modes and their effective refractive indices determine the number and spatial distribution of self-images and strongly depend on the width of the multimode waveguide. Thus, we fabricated a series of MMI structures with different multimode waveguide width varied from 1.7 $\mu$m to 4.5 $\mu$m corresponding to the excitation of $\text{TE}_{02}$ - $\text{TE}_{06}$ highest-order mode. The width of the single-mode waveguide was equal to 0.8 $\mu$m that allows existing only $\text{TE}_{00}$ BSW mode inside the waveguide (\textit{see} Supplementary Information, Section S2). The lengths of single-mode and multimode waveguides were fixed to 15 $\mu$m and 46 $\mu$m, respectively. The grating period was chosen to be 1340 nm to couple the radiation of the 670-nm laser diode with BSW \textit{via} the second diffraction order.
Figure 1: Sample design and experimental idea. a) Schematic of 1D photonic crystal with polymer waveguide structure sustaining Bloch surface wave multimode interference and experimental idea of leakage radiation microscopy. Laser radiation with the wavelength of 670 nm is focused into the coupling grating and excites Bloch surface waves propagating inside the polymer waveguide. Multimode interference pattern formed by guided Bloch surface wave modes and leaked through the substrate is collected from the circled area using an oil-immersion objective lens. b) Schematic representation of a multimode interference structure on the photonic crystal surface. All the elements have the same height of 210 nm.

The effect of multimode interference of BSWs was studied using leakage radiation microscopy (LRM) technique. The scheme of the experiment is shown in Fig. 1a. A collimated beam of 670 nm laser diode was focused by an objective lens (NA= 0.2) into the input grating of the MMI structure at the normal incidence. The radiation polarization was parallel to the bars of the diffraction grating to obtain TE-polarized light in the second diffraction order. Since the double reciprocal grating vector is equal to the wavenumber $k_0$ of the incident light, the wave vectors $\beta$ of BSWs excited by the grating are varied from $k_0$ to 1.2 $k_0$. Thus, the proposed coupling scheme allows one to excite a waveguide mode with the maximum value of effective refractive index $n_{eff} = \beta/k_0 = 1.2$ which is larger than the maximum value $n_{eff}^{max} = 1.13$ of BSW modes that can occur in MMI structures under study. As a result, in the experiment, BSW modes are always excited by the grating inside...
the taper which focuses them into the single mode waveguide. Due to the sufficiently large length of the single mode waveguide, only the fundamental TE$_{00}$ BSW mode reaches the multimode waveguide and initiates the multimode interference.

As BSWs propagate within the waveguides, some part of the radiation leaks into the substrate at angles $\theta$ corresponding to the condition of $\beta = n_{sb}k_0\sin(\theta)$, where $n_{sb} = 1.52$ is the refractive index of the substrate. The intensity of leakage radiation is proportional to the near-field intensity of BSWs. Hence the evanescent electric field distribution of BSWs inside the MMI structure can be visualized by imaging the spatial intensity distribution of leakage radiation. The imaging system was based on oil-immersion objective lens with a high numerical aperture (NA= 1.3) allowing us to collect the leakage radiation of BSW waveguide modes with $n_{eff} \leq 1.3$. The collected light was spatially filtered to block the unwanted radiation passing through or scattered on the diffraction grating. The image of the sample formed by leakage radiation was built on the sensor of CMOS camera. A detailed description of LRM setup is given in the Materials and Methods Section and in the Supplementary Information, Section S3.

**Multimode interference**

Fig. 2a shows the atomic force microscopy (AFM) image of a typical MMI structure and Fig. 2b depicts a cross-sectional view of the wide multimode waveguide. The waveguide has a rectangular shape in the cross-section and its height is $210 \pm 5$ nm. A slight slope of the waveguide walls is most likely related to the finite size of the AFM probe, and the width of the waveguides was determined by the width of its top part. The LRM image of the MMI structure with 3.3 µm wide multimode waveguide is presented in Fig. 2c. Propagating BSW shows behavior typical of MMI of waveguide modes: LRM image is a periodical pattern of intensity maxima. The bright spots correspond to self-images of the input field distribution. The number of self-images in the waveguide cross-section periodically varies along the waveguide. Fig. 2d shows the result of numerical calculations of near-
field distribution within the MMI structure with experimental geometrical parameters. The periodic pattern of BSW near-field intensity perfectly coincides with the experimental LRM image. The details of numerical calculations are provided in the Methods and Materials section.

![Figure 2](image)

**Figure 2:** Multimode interference of Bloch surface electromagnetic waves. a) AFM image of a typical MMI structure fabricated on top of a photonic crystal. b) Cross-sectional AFM view of the multimode waveguide with W = 3.3 µm. The edges by which the waveguide width is determined are marked by vertical dotted lines. c), d) Experimental image of the leakage radiation collected from MMI structure with W = 3.3 µm and corresponding near-field distribution calculated by FDTD method for the waveguide structure of the same geometrical parameters.

We define MMI period $L_{MMI}$ as a longitudinal distance from the beginning of the multimode waveguide to the first single self-image or as the distance between two single self-images. For the system shown in Fig 2 $L_{MMI}$ is approximately 20 µm. The first N-fold image is located at the distance of $L_{MMI}/N$ from the input edge of the waveguide and can be used to implement 1xN splitting. The maximum N value is determined by the number of the highest-order waveguide mode that can be sustained by the multimode waveguide and depends on its width. For example, to create a simple 1x2 MMI coupler we set the length of the multimode waveguide to $L_{MMI}/2$ and align the centers of the output waveguides to the positions of the BSW intensity maxima in the two-fold image (see Supplementary information, Section S4). We denote the distance between these two maxima as $\Delta$. Both $L_{MMI}$ and $\Delta$ are the key parameters in the design of MMI couplers and are governed by the width W of the multimode waveguide. Fig. 3a, b, c demonstrate LRM images measured for
multimode waveguides of different width: \( W = 2.1 \, \mu m, 3.5 \, \mu m, 4.5 \, \mu m \). The first single self-image position continuously shifts from the beginning of MMI waveguide to its end with the \( W \) increase. The distance \( \Delta \) increases with the \( W \) growth as well. To analyze \( L_{MMI}(W) \) dependence we measured the intensity profile along the MMI waveguide center for various \( W \) values. The studied longitudinal section is marked with a horizontal red line in the LRM images. The intensity distribution along the line is a series of peaks and dips associated with odd self-images (single, three-fold, \textit{etc.}) and even self-images (two-fold, four-fold, \textit{etc.}), respectively. Fig.3d shows the experimental results for \( W \) values from 1.7 \( \mu m \) to 4.5 \( \mu m \) with the step of 0.2 \( \mu m \). Each horizontal line in the 3D graph corresponds to the longitudinal intensity distribution along the waveguide with particular \( W \) value. The corresponding BSW near-field intensity profiles calculated as a function of \( W \) are presented in Fig.3e for comparison. With increasing width, a change in the position of the maximum corresponding to the first single self-image is easily observed. Dashed curves in Fig.3e schematically show the evolution of the positions of the first two-fold, first single and second single self-images, demonstrating a non-linear growth of \( L_{MMI} \) distance with the waveguide width increase.

Due to inevitable radiation losses the MMI patterns become blurry moving along the waveguide. The losses associated with the light scattering on inhomogeneities of the waveguide were not taken into account in the calculations that leads to a slight mismatch between LRM intensity and near-field intensity distributions.

Experimental MMI patterns allow us to extract the values of longitudinal distance \( L_{MMI}/2 \) between the positions of all single and two-fold self-images and average them for each \( W \) (see Supplementary Information, Section S5). The obtained dependence of \( L_{MMI}/2 \) on \( W \) is shown in Fig. 3f by red dots. The dependence demonstrates a nearly quadratic growth of the BSW MMI period with the waveguide width increase. \( L_{MMI}/2 \) values taken from FDTD near-field calculations and averaged in the same manner are marked by the blue curve in Fig 3f. The measurements agree well with the calculations indicating that the LRM measurements not only qualitatively but also quantitatively reproduce the calculated near-field
Figure 3: Multimode interference period of Bloch surface waves. a), b), c) (top) LRM images of the waveguides with the width W equal to 2.1 µm, 3.5 µm, 4.5 µm, respectively. (bottom) Leakage radiation intensity distribution along the waveguide center marked by the red line in the LRM image. d), e) Experimental and numerical dependences of the leakage radiation intensity and near-field intensity distributions along the waveguide on its width. Dashed curves indicate positions of the dips and peaks corresponding to the first two-fold, first single, and second single self-images. f) The dependence of the MMI half period $L_{MMI}/2$ on the waveguide width W. Experimental data is shown with red dots, numerical data obtained from FDTD simulation - with a blue curve, numerical data obtained from MPA using Eq. (1) - with a black curve.

distribution of BSW modes in the MMI structures. Note that the BSW scattering losses do not affect the value of the MMI period.

In the same way, we analyze the dependence of distance $\Delta$ between the BSW intensity maxima in the two-fold image on the width of the MMI waveguide. The results are shown in Fig.4. For each W, we measured the intensity profile across the multimode waveguide at the position of the first two-fold self-image. As an example, the LRM image of the 4.1 µm-wide multimode waveguide with the cross-section position marked by the vertical red line and corresponding intensity profile normalized to its maximum intensity are shown in Fig.4a, b, respectively. Combined experimental results for all W values are presented in Fig.4c, where each horizontal line is normalized intensity profile corresponding to particular W value. The
Figure 4: Two-fold self-image characterization. a) LRM image of the waveguide with $W = 4.1 \, \mu m$. Red line is the position of the first two-fold self-image. b) Leakage radiation intensity (red curve) and near-field amplitude (blue curve) distributions in the position of the two-fold self-image. c), d) Experimental and numerical dependences of leakage radiation intensity and near-field amplitude distributions of the two-fold self-image on the waveguide width. e) Dependence of the distance $\Delta$ between BSW intensity maxima in the two-fold self-image on the waveguide width $W$. Experimental data is shown with red dots, numerical data obtained from FDTD simulation - with a blue curve, and numerical data obtained from MPA using Eq. (1) and (2) - with a black line. f) Calculated BSW intensity profiles in cross-section of the single-mode waveguides with various cladding effective refractive indices. Insets show the intensity distribution of TE$_{00}$ BSW mode in the rib and ridge waveguide configurations.

Results of FDTD near-field calculations are given in Fig.4d for comparison. Experimental and calculated dependences $\Delta(W)$ obtained from the intensity profiles are shown by red dots and a blue curve in Fig.4e, correspondingly. The distance between the maxima in the two-fold self-image almost linearly depends on the width of the multimode waveguide.

Multimode interference effects are well described by the guided-mode propagation analysis developed for step-index waveguides, according to which $L_{MMI}$ is proportional to the beat length $L_\pi$ of two lowest order modes:

$$L_\pi = \frac{\pi}{(\beta_0 - \beta_1)} \simeq \frac{4n_r W_e^2}{3\lambda_0},$$

(1)
where $\beta_0$ and $\beta_1$ are propagation constants of these modes (TE$_{00}$ and TE$_{01}$ in our case), $n_r$ is an effective refractive index of the waveguide core (which corresponds to the effective refractive index $n_{\text{eff}}^{\text{max}}$ of the BSW in polymer film on top of the PC in our case, see Supplementary Information, Section S2), $W_e$ is an effective fundamental mode width, which is proportional to the waveguide width $W$, and $\lambda_0$ is the wavelength of incident radiation in vacuum. In our case, the input waveguide enters the center of the multimode waveguide resulting in the excitation of even symmetric modes only. This symmetric interference has the minimum value of the MMI period of $L_{\text{MMI}} = 3L_\pi/4$. It is easy to find the $L_{\text{MMI}}(W)$ dependence calculating the difference $n_{\text{eff}}^{\text{TE}_{00}} - n_{\text{eff}}^{\text{TE}_{01}}$ between effective refractive indices of two lowest order modes using any eigenmode solver (we used Lumerical FDE solver). The result for $L_{\text{MMI}}/2(W)$ is presented in Fig.3f by the black line. The perfect agreement of numerical results with the ones obtained from the experiment and the FDTD calculations indicates that BSW propagating in MMI waveguides is successfully described by the mode propagation analysis (MPA) originally developed for conventional step-index waveguides.

According to MPA approach, the distance $\Delta$ should be exactly equal to the half of the width $W_e$ of fundamental waveguide mode: \(^{40}\)

$$
\Delta = \frac{W_e}{2} = \frac{W}{2} + \frac{\delta W}{2}
$$

(2)

$$
\delta W = \frac{\lambda_0}{\pi \sqrt{n_r^2 - n_c^2}},
$$

(3)

where $\delta W$ is the penetration depth of the BSW mode field into the cladding material, and $n_c$ is effective refractive index of the cladding. We calculated $W_e$ for each $W$ using the Eq. (1) and obtained $\Delta(W)$ dependence, which is shown in Fig. 4e by black curve and is in good agreement with the measurements and FDTD calculations. Using Eq. (2) we found $\delta W/2 = 65$ nm from this dependence. The best linear fit of the experimental $\Delta(W)$ dependence by the Eq. (2) provides $\delta W/2 = 89 \pm 18$ nm which is quite close to the calculated value. Further, the mean value of refractive index contrast $n_r^2 - n_c^2 = 2.7$ is calculated using Eq. (3).
with the experimental value of \( \delta W/2 = 89 \) nm. Given that \( n_r = n_{c_{\text{max}}} = 1.13 \), we conclude that the cladding effective refractive index \( n_c \) is a complex number with a large imaginary part. This is because the medium outside the waveguide acts like PC in the band gap region, since bare PC does not support BSWs outside the waveguide. In situation when PC sustains BSW inside and outside of waveguide,\(^{13,32,34} \) \( n_c \) is equal to BSW \( n_{c_{\text{eff}}} \) on a bare PC as was demonstrated in BSW refraction experiments.\(^{49} \) In addition, \( n_r \) can be controlled more or less independently of \( n_c \) by the choice of the waveguide height. Such flexibility can be shown by the example of our PC. Lets consider two types of single-mode waveguides with the same width of 0.8 \( \mu \)m. The first type is the ridge waveguide studied in this paper. The second one is a rib waveguide of 60 nm height located on a 150 nm thick polymer layer that covers the PC. Waveguide effective refractive index \( n_r \) is the same in both cases, but the values of \( n_c \) are different since in the second case the PC/polymer layer structure sustains BSW with \( n_{c_{\text{eff}}} = 1.01 \) outside the rib waveguide. Fig. 4f demonstrates intensity distribution of BSW fundamental mode in the waveguides cross-section at the height of 160 nm from Ta\(_2\)O\(_5\) layer. The lateral field confinement is better in the ridge waveguide since the index contrast \( n_r^2 - n_c^2 \) is higher in this case. Thereby, BSW integrated platform provides a unique opportunity to choose the desired refractive index contrast from hundredths and tenths to several units, \( i.e. \) implement low or high contrast system based on ones purposes. This can be useful, for example, in managing the evanescent coupling of waveguides placed in close proximity since the greater is the contrast the weaker the interaction between the waveguides is.

**Mach-Zehnder interferometer**

We demonstrated the possibility to control BSW using MMI effect by creating compact Mach-Zehnder interferometers (MZIs) with desirable phase shift between BSW modes propagating in two arms without curved parts. MZI consisting of 1x2 and 2x1 MMI couplers connected by two arms with different optical paths for fundamental BSW mode is shown in Fig.5a. The necessary phase shift is provided by 1x1 MMI coupler in one of the arms.
Effective refractive index of a waveguide mode rises with the increase of the waveguide width. Thus, the phase shift in the arm of the interferometer can be induced by the waveguide with different width put in the arm. The value of the phase shift is defined as the follows:

\[ \Delta \varphi = \frac{2\pi}{\lambda_0} (n_{\text{TE}00}^{\text{eff}}(W_{ps}) - n_{\text{TE}00}^{\text{eff}}(W_{arm})) L_{ps} \]  

(4)

where \( n_{\text{TE}00}^{\text{eff}}(W_{arm}) \) and \( n_{\text{TE}00}^{\text{eff}}(W_{ps}) \) are effective refractive indices of fundamental TE\(_{00}\) mode in narrow and wide parts of waveguides with the width of \( W_{arm} \) and \( W_{ps} \), respectively, \( L_{ps} \) is the length of the wide waveguide part, and \( \lambda_0 \) is the wavelength of the light in vacuum.

The specific phase shift \( \Delta \varphi \) can be achieved by infinite set of configurations of \((W_{ps}; L_{ps})\). However, shorter values of \( L_{ps} \) are preferred for compact MZI device. This can be achieved by increasing the difference of \( n_{\text{eff}} \) in Eq. (4), which grows with the increase of \( W_{ps} - W_{arm} \) widths’ mismatch. On the contrary, the increase of \( W_{ps} \) leads to the MMI effect. The critical width \( W_{ps} \) of the wide waveguide for studied BSW structures is equal to 1.6 \( \mu \)m when TE\(_{02}\) mode can be excited. With the further increase of \( W_{ps} \), we have to fix the length \( L_{ps} \) equal to \( L_{\text{MMI}}(W_{ps}) \) in order to avoid losses. As a result, the wide part of the waveguide becomes 1x1 MMI coupler, and the specific phase shift is achievable only for a unique configuration of \((W_{ps}; L_{ps})\) (see Supplementary Information, Section S6).

We designed two MZIs with the phase shift of 0 and \( \pi \). In the 0-phase-shift case, two MZI arms are identical single-mode waveguides with the constant width \( W_{arm} = 0.8 \) \( \mu \)m and the length of 10 \( \mu \)m. The \( \pi \)-phase-shift MZI contains a section of the wide multimode waveguide with the width \( W_{ps} = 1.9 \) \( \mu \)m and the length \( L_{ps} = 7 \) \( \mu \)m, which is embedded in the single-mode waveguide of one of the arms, as shown in the AFM image in Fig. 5b. The distance between the phase shift waveguide and the second arm waveguide is fixed to 0.5\( \mu \)m to eliminate a potential crosstalk between them. This results in the distance of 1.9\( \mu \)m between output waveguides of the 1x2 coupler. Using experimental dependences of \( L_{\text{MMI}}(W) \) and \( \Delta(W) \) from Fig.3f and Fig.4e we have found the width and length of 1x2 MZI couplers,
which are $3.6 \mu m$ and $11.4 \mu m$, respectively. Experimental LRM images as well as numerically calculated near-field intensity distributions in two MZIs are shown in Fig.5 c,e and Fig.5 d,f, respectively. Constructive and destructive interference in the output waveguide is clearly seen for MZIs with phase shifts of 0 and $\pi$, correspondingly. The experimental LRM field distributions are in a good agreement with the near-field distribution calculated by FDTD. This result demonstrates an unprecedented ability to control and manipulate visible light at the micro-scale using BSW concept.

![Figure 5](image-url)

**Figure 5:** Mach-Zehnder interferometers for Bloch surface waves. a) Scheme of MZI with a non-zero phase shift between the BSW modes propagating in different arms. b) AFM image of MZI with the phase shift of $\pi$. c), e) Experimental LRM images of the right part of MZIs with the phase shift of 0 and $\pi$, respectively. d), f) Calculated near-field distribution in the right part of MZIs with the phase shift of 0 and $\pi$.

**Discussion**

We have experimentally demonstrated the effect of multimode interference of Bloch surface waves by a direct visualization of the interference pattern using leakage radiation microscopy technique. We measured the dependences of the MMI period and the distance between two images in the first two-fold self-image on the width of the multimode waveguide. To the best of our knowledge this is the first comprehensive experimental study of the multimode interfer-
ence effect in waveguide structures. Excellent qualitative and quantitative agreement of the experimentally measured leakage radiation intensity distributions in a multimode waveguide with the near-field distributions obtained from 3D FDTD simulations is demonstrated. This confirms wide possibilities of the LRM method to determine the near-field characteristics of leaky modes. We have also shown that MMI of BSWs with a complex field distribution inside the PC is perfectly described by the mode propagation analysis that was originally developed for the bulk guided modes propagating in step-index waveguides. This allows us to estimate the size of the MMI couplers without resorting to time-consuming three-dimensional simulations, but using the effective refractive indices of the first two modes, which can be obtained with the eigenmode solvers. Finally, based on the results of studying the MMI effect, we demonstrated Mach-Zehnder interferometers with a predefined phase difference between the BSWs propagating in different arms. Interferometers operate in the visible wavelength range and do not contain the curved parts.

We used the PC comprising only 5 pairs of layers in order to obtain the BSWs with sufficient radiation losses and make it easy to detect through the leakage radiation. However, the radiation losses decrease exponentially with increasing the number of PC periods and can be made negligible. For example, the recent study experimentally demonstrates the BSW with the losses of only 3 dB/cm at the wavelength of 633 nm,\textsuperscript{14} which is one or two orders of magnitude smaller than the losses reported for all types of surface electromagnetic waves in the visible and comparable with losses of Si\textsubscript{3}N\textsubscript{4} waveguides.\textsuperscript{50} This makes the BSW platform very promising for its application in visible integrated photonics, development of which is essential in areas such as quantum optics, harmonic generation, on-chip light sources, and biosensing. Notably, the proposed photonic devices sustain the guided modes with a quite low effective refractive index close to unity. Despite this, BSW MMI elements are comparable in size to typical MMI structures for high-refractive-index SOI platform.\textsuperscript{51} This is consistent with Eq. (1) according to which the MMI period determining the size of MMI device decreases with a decrease in the effective refractive index of multimode waveguide.
with fixed width. Such a counterintuitive dependence actually results from a decrease in the number of interfering modes supported by the multimode waveguide. In turn, the ability to use the smallest possible number of modes, when designing couplers with a large number of inputs and outputs, is an important advantage of BSW MMI devices, because it allows us to minimize the influence of the phase errors occurring for high-order modes\(^{52}\) and improve the performance of large couplers without tricks such as expanding input-output waveguides or creating sub-diffraction structuring.\(^{53}\) The possibility of BSW platform to easily design the effective refractive index contrast by simply adjusting the thicknesses of PC layers and top structured layer enables us to further reduce the phase errors for higher-orders waveguide modes.\(^{54}\)

In summary, our work is a clear demonstration of how well the visible light can be manipulated on a micrometer scale just using conventional dielectric materials and simple structuring techniques. BSW platform provides unique opportunities to design the integrated photonic circuits for specific spectral ranges, in which SPP or SOI platforms suffer from absorption. The BSW devices under the development can be easily inspected at the prototyping stage by the LRM technique that allows visualizing the influence of defects and fabrication errors on the near-field distribution inside the devices. The confinement of the BSW field near the top of a waveguide (unlike dielectric-loaded surface plasmon-polaritons\(^7\)) ensures its sensitivity to the environment, which reveals the way of implementing BSW-based integrated optical sensors for applications in biology and medicine. Moreover, the ability to use polymers as a waveguide core material allows us to incorporate various types of luminescence or nonlinear materials, such as quantum dots, directly into the waveguides. We believe that the proposed MMI concept can form the foundation of a new type of integrated optical devices that are applicable to a number of key tasks, such as integrated single-photon sources\(^{55}\) and on-chip quantum circuits,\(^2\) and integrated photonic sensors\(^{56}\) including multimode interference devices for sensing.
Methods

Photonic crystal samples

One-dimensional photonic crystal (PC) is designed to sustain TE-polarized BSW at \( \lambda = 670 \) nm in the presence of an additional layer of polymer on its surface (see Section S1 of Supplementary materials for more information). It consists of 5 pairs of SiO\(_2\) \( (n_{SiO_2} = 1.45 \) at \( \lambda = 670 \) nm) and Ta\(_2\)O\(_5\) \( (n_{Ta_2O_5} = 2.09 \) at \( \lambda = 670 \) nm) alternating layers sputtered on a BK-7 glass coverslip \( (n_{s_b} = 1.52) \) with the thickness of 170 \( \mu \)m. The thicknesses of SiO\(_2\) and Ta\(_2\)O\(_5\) layers are 140 nm and 98 nm, respectively. The terminating layer of PC is Ta\(_2\)O\(_5\). The thickness of the polymer film on the PC surface is important parameter and defines the height of the waveguides. In order to make a thin film the photoresist SU-8 2015 (Microchem, \( n_{SU−8} = 1.58 \)) is firstly diluted with SU-8 developer of mr-DEV 600 (Microchem) in a ratio of 15:85 and the obtained solution is spin coated at 3000 rpm to obtain 210 nm thick polymer layer.

MMI samples fabrication

Fabrication procedure of MMI samples consists of 5 steps: photoresist film spin-coating, prebaking at 95°C for 45 minutes (solvent evaporation), exposure (writing), baking at 95°C for 15 minutes (SU-8 polymerization), developing in mr-dev600. Exposure is performed with the custom two-photon laser lithography setup.\(^{35}\) Radiation from femtosecond Ti:sapphire laser source (Coherent Vitara, \( \lambda =800 \) nm, 50 fs pulse duration, 80 MHz repetition rate) is focused on the PC surface with an air objective lens (NA=0.95, 100X, LOMO) mounted on a piezo stage (Newport NPO250SG). Fast steering mirror (Newport FSM300) combined with 4f -system provides rapid lateral beam movement. Acousto-optic modulator (Isomet M1099-T80L-3) is used as a fast beam shutter. The writing trajectories are straight lines. Grating hatches and single-mode waveguides are single lines, tapers consist of an array of lines with smoothly changing length. Multimode waveguide is an array of parallel lines with the same
length. The distance between subsequent lines in arrays is 200 nm. The width of multimode waveguides is controlled by the number of parallel lines with an accuracy of less than 30 nm. The writing speed is $10 \, \mu m/s$ and average power at the entrance of the objective lens is 15 mW. Writing is performed in an overexposure regime resulting in a waveguide profile close to the rectangular shape as can be seen in Fig.2b.

**MMI samples**

MMI structures consist of a diffraction grating, taper, narrow input single-mode waveguide, wide multimode waveguide, and narrow output waveguide. The diffraction grating contains 6 hatches with period of 1340 nm. The taper is an isosceles triangle with the base of 5 $\mu m$ and the length of 6 $\mu m$. The input 0.8 $\mu m$ waveguide is located in the middle of wide multimode waveguide. This design implements so-called symmetric mechanism of interference\(^3\) providing the shortest MMI period. The length of both input and output waveguides is equal to 15 $\mu m$. The length of the multimode waveguide is 46 $\mu m$, while the width W is varied from 1.7 $\mu m$ to 4.5 $\mu m$ with 0.2 $\mu m$ step. For each W, we fabricated 5 MMI structures with the same parameters to then average the results for the $L_{MMI}/2$ and $\Delta$ over identical samples. The geometrical parameters of MZI diffraction gratings, tapers and single-mode waveguides are equal to those described above.

**Leakage radiation microscopy**

MMI structures and MZIs are characterized using leakage radiation microscopy. LRM allows visualization of BSW propagation as well as wavevector distribution of BSW modes. A collimated beam of 670 nm laser diode (Thorlabs CPS670F) is focused by an objective lens (NA = 0.2, 10X, Lomo) mounted on a 3-axis stage into the input grating of MMI structure at the normal angle of incidence. The polarization of the incident radiation is controlled by Glan-Taylor prism. The imaging part of LRM setup is based on an oil immersion objective lens with a high numerical aperture (NA = 1.3, 100X, Olympus UPLFLN100XOI2) allowing
us to collect TE-polarized leakage radiation of BSW waveguide modes with $n_{eff} \leq 1.3$. The collected light passes through $4f$-system in order to perform two-stage filtering in real and $\mathbf{k}$-space. This system constructs intermediate images of front and back focal planes of the collecting objective lens. Filtering is done with an aperture and slit located in the intermediate images of front and back focal planes of the objective lens, respectively. At the first filtering stage, the aperture selects a part of collected radiation that comes only from the MMI region of waveguide structures (dotted line in the Fig. 1). At the second stage, the slit selects the radiation with the value of the tangential component of wavevector from $k_0$ to $1.2 k_0$. The back focal plane image of leakage radiation of BSW waveguide mode is a strip perpendicular to the direction of BSW propagation. Thus, the edges of the slit are oriented in parallel to the stripes to pass all the leakage radiation. After filtering, the front and back focal plane images are constructed on the sensors of two different CMOS cameras (Thorlabs DCC1545M) allowing us to study BSW field and wavevector distribution simultaneously. The polarization of collected radiation is controlled by a film polarizer. The additional information on LRM setup is provided in the Supplementary Information, Section S3.

Calculations

Numerical calculations are performed with the commercial Lumerical FDTD software. Simulation area is set to be 3D. SiO$_2$ and Ta$_2$O$_5$ PC layers are modeled as dielectrics with refractive indices equal to 1.45 and 2.09 and thicknesses of 140 nm and 98 nm, respectively. The PC is on a glass substrate with refractive index equal to 1.52 and thickness equal to 2 $\mu$m. Polymer waveguides (single-mode and multimode) are modeled as a ridge with refractive index equal to 1.58. The height of the waveguides is fixed to 210 nm during calculations. Firstly, we study BSW modes of a polymer waveguide with the Lumerical FDE solver. A two-dimensional slice of the PC with the waveguide at the top is used to evaluate BSW modes sustained by the waveguide. Thus, we obtain effective refractive indices for all modes.
supported by a waveguide with a particular width. Then we evaluate the dependence of TE\textsubscript{00} and TE\textsubscript{01} BSW mode effective refractive indices on the waveguide width. These data are used to calculate MMI half period \( L_{MMI}/2 \) and effective waveguide width \( W_e \) using Eq. 1-3 (see Supplementary Information, Section 2). Then, TE\textsubscript{00} BSW mode is launched into the input single-mode waveguide of the studied MMI structure to perform 3D FDTD simulation. The model of the MMI structure on top of the PC consists of the input single-mode waveguide with the length of 5 \( \mu \)m and the width of 0.8 \( \mu \)m and the wide multimode waveguide with the length of 46 \( \mu \)m and the width varied from 1.7 \( \mu \)m to 4.5 \( \mu \)m. The near-field distribution is measured in the plane parallel to the PC surface and located at the distance of 160 nm above the PC surface. This position corresponds to the maximum of the BSW electromagnetic field intensity. The simulation volume is enclosed in Perfectly Matched Layers (PML) boundary condition.

**Acknowledgement**

This work was partly supported by Russian Ministry of Education and Science (14.W03.31.0008, photonic crystal fabrication and leakage radiation microscopy setup), Russian Foundation for Basic Research (18-32-00869, 18-32-00841) and MSU Quantum technology centre.

**Supporting information**

Supporting text and figures are available free of charge via the Internet at http://pubs.acs.org.

Numerical design of the photonic crystal; Effective refractive indicies of BSW waveguide modes and the proof of the applicability of the mode propagation analysis to the BSW mode description; Scheme and detailed description of the leakage radiation microscopy setup; Demonstration of 1x2 multimode interference BSW splitter; Description of camera images processing for determination of multimode interference parameters; Design of a multimode interference BSW phase shifter.
Author contributions

K.R.S. initiated research and performed calculations. K.R.S., V.O.B., and A.A.F. conceived and planned the experiments. V.O.B. designed leakage radiation microscopy setup. D.N.G. conducted leakage radiation microscopy experiments. I.M.A. prepared thin polymer films and performed atomic force microscopy measurements. K.A.A. and K.R.S. fabricated BSW waveguide samples. K.R.S., V.O.B., and A.A.F. wrote the manuscript, D.N.G. compiled the figures. All authors contributed to the discussion of the results and the manuscript. V.O.B. and A.A.F. supervised the entire project.

Conflict of interest

The authors declare that they have no conflict of interest.

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Graphical TOC Entry