Published in final edited form as:

ACS Nano. 2017 October 24; 11(10): 10446–10451. doi:10.1021/acsnano.7b05638.

Silver Nanowires for Reconfigurable Bloch Surface Waves

Douguo Zhang^{1,*}, Ruxue Wang¹, Yifeng Xiang¹, Yan Kuai¹, Cuifang Kuang²,
Ramachandram Badugu³, Yingke Xu⁴, Pei Wang¹, Hai Ming¹, Xu Liu², and Joseph R.
Lakowicz³

¹Institute of Photonics, Department of Optics and Optical Engineering, University of Science and Technology of China, Hefei, Anhui, 230026, China

²State Key Laboratory of Modern Optical Instrumentation, Department of Optical Engineering, Zhejiang University, Hangzhou 310027, China

³Center for Fluorescence Spectroscopy, Department of Biochemistry and Molecular Biology, University of Maryland School of Medicine, Baltimore, MD 21201, United States

⁴Department of Biomedical Engineering, Key Laboratory of Biomedical Engineering of Ministry of Education, Zhejiang Provincial Key Laboratory of Cardio-Cerebral Vascular Detection Technology and Medicinal Effectiveness Appraisal, Zhejiang University, Hangzhou 310027, China

Abstract

The use of a single silver nanowire as a flexible coupler to transform a free space beam into a Bloch surface wave propagating on a dielectric multilayer is proposed. Based on Huygens' Principle, when a Gaussian beam is focused onto a straight silver nanowire, a Bloch surface wave is generated and propagates perpendicular to the nanowire. By curving the silver nanowire, the surface wave can be focused. Furthermore, the spatial phase of the incident laser beam can be actively controlled with the aid of a spatial light modulator, resulting in the reconfigurable or dynamically controlled Bloch surface waves. The low cost of the chemically synthesized silver nanowires and the high flexibility with regard to tuning the spatial phase of the incident light make this approach very promising for various applications including optical micromanipulation, fluorescence imaging, and sensing.

Graphical Abstract

Deflecting the Bloch Surface Wave with a silver nanowire and the structured incident beam by a spatial light modulator.

Correspondence and requests for materials should be addressed to D.G. Zhang. dgzhang@ustc.edu.cn.

Competing financial interests: The authors declare no competing financial interests.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI:XXX. Numerical simulation of BSW excitation by a Gaussian beam, BSW excited by the defocused Gaussian beam, influence of the focusing objective lens, influence of the q value on the deflection angle of the excited BSW, back focal plane images of the reconfigurable BSW, BSW needle excited by two crossed Ag nanowires, are all presented in the supporting information.

Keywords

silver nanowires; reconfigurable Bloch surface wave; dielectric multilayer; spatial light modulator

Chemically synthesized silver nanowires with crystalline structures can be fabricated very easily and at very low cost; they have commonly been used as efficient plasmonic waveguides because of their smooth surfaces.^{1, 2} By focusing light onto one end of the silver nanowire with a microscope objective or a fibre taper, surface plasmons (SPs) are efficiently excited at this end and transmitted to the other end.^{3, 4} They perform the same function as an optical fibre but with deep subwavelength field confinement; they can also be used to construct various plasmonic devices, such as plasmonic routers or logic gates, which can be integrated with nano-electronic devices for high-speed nano-photonics circuitry.⁵⁻⁷ Because of these properties, silver nanowires have been widely investigated for applications in plasmonics and nano-photonics. In this paper, we demonstrate that a single silver nanowire also can operate as a flexible coupler to convert free space light into localized surface waves propagating on a dielectric multilayer when an incident beam is focused onto the centre of the silver nanowire. This kind of surface wave is referred to as a Bloch surface wave (BSW), which is an electromagnetic surface wave excited at the interface between a truncated periodic dielectric multilayer and the surrounding medium.^{8, 9} BSWs have similar properties to SPs on a metal film, such as enabling optical near-field confinement and enhancement, being sensitive to the environment, and having larger wave-vectors than light of the same frequency in a vacuum. Therefore, BSWs have been considered the dielectric analogue of SPs but with lower losses because of the lower absorption losses of dielectrics compared with metals.¹⁰ However, to the best of our knowledge there have been no reports on reconfigurable BSWs until now. The reconfigurable BSW can be used as an in-plane virtual probe in fluorescence microscope to selectively excite the fluorophores, and also it can work as a dynamic optical tweezers.

Similar to SPs, BSWs are excited with subwavelength gratings inscribed on the top surface of a dielectric multilayer to satisfy momentum matching conditions.¹¹⁻¹⁴ However, the cost for fabricating the gratings with focused ion beam or electron beam lithography is relatively high. Furthermore, the inscribed grating is fixed and thus it is difficult to change or tune its spatial position and structural parameters; further, it cannot be reused. To solve this problem, we deposited a chemically synthesized silver nanowire onto a dielectric multilayer. Silver nanowires exhibit strong surface plasmon resonances under photo-illumination because of the strong coherent oscillation of the nanowires' free surface electrons, which results in their ability to strongly scatter incident light. These scattered signals are transformed into BSWs, thereby providing an approach for the excitation of surface waves.

RESULTS AND DISCUSSION

Figure 1 shows a schematic of the experimental setup for exciting and imaging the BSWs. A dielectric multilayer made of alternating layers of SiO_2 and Si_3N_4 was fabricated with plasma-enhanced chemical vapour deposition; the thicknesses of each layer are detailed in Figure 1 (a) and described in the methods section. The medium contacting the multilayer's top surface was deionised water. The silver nanowires employed in this research had diameters of approximately 120 nm (Figure 1 (d)) and were synthesized through a wet chemistry approach. An individual nanowire was deposited on the above-mentioned multilayer (Figure 1 (c)). Figure 1 (a) shows a schematic of the experimental setup. A laser beam with a wavelength of 640 nm was reflected from a spatial light modulator (SLM) and then focused onto the silver nanowire from above with an objective (objective-1, Figure 1 (a)). The leakage radiation of the excited BSWs was collected by another objective (objective-2, 100 $\times$ and N.A. 1.49) below the dielectric multilayer and then imaged onto charge-coupled device cameras to capture the propagation of the BSW.

BSWs excited by the Gaussian beam and focusing BSW by a curved silver nanowire

When the SLM is turned off or replaced with a mirror (Figure 1 (a)), the incident laser beam has a Gaussian shape. The Gaussian beam was focused onto the centre of the silver nanowire (Figure 2(a)), generating a distinct BSW that propagates in a straight line (Figure 2(b)). The propagation direction is perpendicular to the long axis of the nanowire. If there are obstacles on the dielectric multilayer along the travelling path, as shown in Figure 2 (c), the BSW will be scattered or diffracted and the BSW will diverge after passing the obstacles (Figure 2 (d)). This phenomenon clearly demonstrates that the excited wave propagates along the surface of the multilayer. In experiment, the combination of a polarizer and a half wave plate is used to control the polarization orientation of the incident laser beam (Figure 1). When the incident polarization is coincided with long axis of the silver nanowire (Supplementary Figure 1 (a)), the excitation efficiency of the BSW will be the maximum, and when the polarization is perpendicular to the nanowire (Supplementary Figure 1 (a)), the BSW cannot be efficiently excited. So, in the following experiment, the half wave plate is rotated to achieve efficient excitation of the BSW. This sensitivity to the incident polarization is due to the polarization state of the BSW sustained by the dielectric multilayer. In this experiment, the BSW is of transverse electric (TE) polarization, which is determined by the structural parameters of the dielectric multilayer.^{10–11, 13–16}

The BSW can be focused if the silver nanowire is curved (Figure 2 (e) and (f)); when the curvature of the nanowire is increased (Figure 2 (g)) the focal length is shortened (Figure 2 (h)). The highly focused BSW has an oval, needle-like shape, as can be seen in Figure 2 (h). Here the silver nanowire can work the same function as a dielectric plano-convex lens fabricated on a dielectric multilayer to focus a BSW.^{10, 15} The nanowire can be moved or adjusted to any place on the multilayer. In addition to focusing the BSW, the curved silver nanowire itself also functions as a coupler to transfer free space light into the BSW.

The Huygens 'Principle can be used as follows to describe the physics underpinning of the above-mentioned experimental results: first, when the laser beam is focused onto the silver nanowire, the strongly scattered light in the near-field region has many wave-vectors. When

the wave-vector is matched with that of the BSW on this multilayer, the scattered light is transferred into the BSW (this has also been verified by numerical simulations, see Supplementary Figure 2, The numerical simulations also show that the diameter and materials of the nanowire, incident polarization all affect the excitation efficiency of the BSW, and the curvature of the silver nanowire will affect the focal length of the BSW. The beam waist of the incident Gauss beam will affect the width and divergence of the BSW). Second, the multilayer is on the focal plane of objective-1, so the silver nanowire is coincident with the waist of the focused Gaussian beam. The waist of a Gaussian beam is an equiphase surface, *i.e.*, every optical spot on the waist has the same phase. Thus, every illuminated spot on the silver nanowire can be regarded as an initial point source of the BSW, and every spot has the same initial phase. As illustrated in Figure 2 (i), points P1, P2, and P3 have the same phase (Here, point P1 is at the centre of the focal spot of the laser beam, P2 and P3 at the edge of the focal spot, they are all the selected points of the Ag nanowire). Based on Huygens 'Principle,¹⁷ the excited BSW will propagate perpendicular to the nanowire; this is consistent with our experimental results (Figure 2 (b)). When the silver nanowire has a curved shape, the focusing of the excited BSW also can be explained by Huygens 'Principle, as illustrated in Figure 2 (j).

In our experiment, the silver nanowire can be illuminated by a defocused beam by moving objective-1 down or up to change the location of the focal plane. The initial phase of every point source on the silver nanowire will be different when illuminated by a defocused beam, resulting in a diverging BSW, as shown in Supplementary Figure 3. By using an objective lens with a different magnification factor for objective-1 it is possible to tune the beam width of the excited BSW as this changes the size of the focal spot (Supplementary Figure 4).

Dynamical tuning the propagating direction of the BSWs with the spatial light modulator

The above-mentioned results verify that a silver nanowire can function as a coupler to transfer free space light into the BSW and that the spatial phase distribution of the illumination source modulates the propagation of the excited BSW. This is an intriguing approach for a reconfigurable BSW: the spatial phase or intensity distribution of the beam striking the nanowire can be tuned with a spatial light modulator (SLM), as shown in Figure 1. The hologram loaded on the SLM can be quickly and stably tuned to achieve a reconfigurable BSW. To verify this approach, a linearly varying spatial phase shift $T(x) = \exp(i2\pi x/x_0)$, $x_0 = q \times \Delta x$, $\Delta x = 8 \mu\text{m}$, where T is the spatial phase, x represents the spatial position, x_0 is an adjustable scale factor, and q is an integer, and $\Delta x = 8 \mu\text{m}$ denotes the pixel size of the SLM, is loaded on the SLM and projected onto the silver nanowire (Figure 3 (b) and (d)). As the phase decreases linearly from point P1 to P3 (Figure 3 (f)), the excited BSW is deflected upwards ($q = 80$, Figure 3 (b) and (c)) with a deflection angle θ of approximately 14° . However, as the phase increases linearly from P1 to P3, the BSW is deflected downwards ($q = -80$, Figure 3 (d) and (e)) with a deflection angle θ of approximately -11° . These phenomena are in agreement with Huygens 'Principle, as illustrated in Figure 3 (f). Furthermore, from the phase distribution equation, $S = 2\pi \times x/x_0$, $xr_0 = q \times \Delta x$, it can be seen that as the value of q increases, the slope of the linear plot of the phase changes along the nanowire decreases. Therefore, the q value is associated with the deflection angle θ . A positive or negative value of q thus corresponds to the upwards or downwards deflection of

the BSW beam, respectively. When we increased the value of $|q|$, the deflection angle decreased, as shown in Supplementary Figure 5; q values of 200 and 400 were studied.

Tuning the width, length, and position of the BSW needle with the spatial light modulator

A more complex phase distribution can be used, such as a hologram, which is commonly used to generate a free space Bessel function beam, which is a non-diffracting beam. A hologram has an angular phase shift that can be described by $T(r, \vartheta) = \exp(in\vartheta) \exp(-i2\pi r/r_0)$, $r_0 = q \times \lambda$, $\lambda = 8 \mu\text{m}$, where ϑ and r are coordinates in the hologram's plane, r_0 is an adjustable scale factor, q is an integer denoting the number of pixels covered by the hologram, and n is an integer showing the order of the Bessel beam.¹⁸ Using two lenses (one lens is loaded on the SLM and the other is objective-1), the spatial phase distribution loaded on the SLM can be projected onto the focal plane of objective-1. When n is zero, there is no phase singularity, so the focal spot created by objective-1 is solid (inset graphs in Figure 4 (c) and (e)). The silver nanowire lies in the centre of the focal spot of the laser beam in this focal plane. Therefore, the phase distribution along the nanowire follows the same pattern as that of the hologram (Figure 4 (b) and (d)). As illustrated in Figure 4 (g), the phase linearly decreases from position P2 (the point P2 is at the centre of the focal spot, shown in Figure 4 (h)) to position P1; it also decreases from P2 to P3 (Figure 4 (h)). Based on Huygens' Principle, the BSW launched from the segment of the Ag nanowire given by the line from P1 to P2 (top segment) deflects downwards, and the BSW launched by the nanowire segment from P2 to P3 (bottom segment) will deflect upwards, as illustrated in Figure 4 (h). As a result, these two BSWs will overlap in a region (indicated with dark lines) and interfere, thus forming an in-plane optical needle (Figure 4 (c) and (e)).^{19–21} For a small q value, such as $q = 80$, the deflection angle of the excited BSW is large, so the needle is short and narrow (Figure 4 (c)) because of the short interference region (Figure 4 (h)). For a large q value ($q = 160$), the deflection angle is smaller, inducing a wide, long optical needle (Figure 4 (e)). When the value of n is 2, a spiral phase will be loaded (Figure 4 (f)), and the phase singularity induces a donut shape at the focal spot (inset graph in Figure 4 (g)).²² In this case, the centre lobe of the BSW needle will be formed a short distance away from the silver nanowire (Figure 4 (g)); the formation principle is illustrated in Figure 4 (i).

As illustrated in Figure 4 (h) and (i), that the formation process of this BSW needle is the same as for a non-diffracting BSW or cosine-Gauss plasmon beam;^{19–21} however, the BSW needle here is not rigorously diffraction-free. The reason for this is that neither the BSWs launched by the top (P2 to P1) or bottom (P2 to P3) segments of the silver nanowire are plane waves because of the finite width of the focal spot. Therefore, the BSWs propagate to the right with a small divergence angle; this has been verified *via* back focal plane images of the propagation of the BSWs (Supplementary Figure 6).^{19, 23} Based on the formation principle illustrated in Figure 4 (h) and (i), we also demonstrate that this kind of BSW needle can be formed with two crossed silver nanowires, as shown in Supplementary Figure 7, and that the width and length of this needle can be tuned by adjusting the cross angle of the two silver nanowires.

It should be noted, similar as the SPs, the BSW also have the ability to squeeze the incident wavelength, meaning that the wavelength of the BSW is smaller than that of light in free

space at the same frequency. So, the focal spot of BSW can break the diffraction limit, the same as the focusing of a Plasmonic wave. However, in the experiment, the incident laser beam is focused by a traditional objective (Figure 1), and its focal spot is diffraction limited and within the constraint of paraxial optics, so the tuning of width, length of BSW is also within the constraint of paraxial optics and the width of the shaped BSW is limited by the diffraction, which also happens in the reported work on shaping the Plasmonic waves.¹⁹

CONCLUSIONS

In conclusion, we have demonstrated an application for chemically synthesized silver nanowires as low cost and flexible couplers to transfer free space light into a BSW on a dielectric multilayer. With the aid of an SLM, the spatial phase distribution of a free space laser beam is modulated; then, the shaped beam is projected onto the silver nanowire, which is placed on a dielectric multilayer. The modulated spatial phase distribution is encoded by the silver nanowire; as a result, the excited BSW is shaped accordingly. Thus the generated BSW can be dynamically controlled owing to the reconfigurable properties of the hologram loaded on the SLM. Additionally, our experimental results show that if a precise micromanipulator is used to tune the position and orientation of the silver nanowires, the propagation of the excited BSW can be adjusted. The reconfigurable BSW could potentially be applied in a water environment as an in-plane dynamic optical tweezer for cells or micro- and nanoparticles. The spatial location of this kind of in-plane tweezer can be tuned through the SLM stably and quickly. It could also be used as an in-plane virtual probe to dynamically excite fluorophores; this virtual probe could be switched on or off and its width, length, and orientation could all be tuned dynamically, which would be applied in fluorescence-based sensing and imaging methods. Whereas, for the previously reported BSW applied in fluorescence sensing and imaging, the generated BSW field is fixed and cannot be tuned to selectively excite the fluorophores. When compared with the total internal reflection fluorescence microscopy for investigating all surface bounded targets inside a field of view, the reconfigurable BSW needle can be used to dynamically investigate the area of interest without influencing or receiving influence from other areas, which results in very low background noise.

METHODS

Sample preparation

The dielectric multilayers were fabricated *via* plasma-enhanced chemical vapour deposition (Oxford, Plasma Pro System 100) of SiO₂ and Si₃N₄ on a standard microscope cover glass (0.17 mm thickness) at a vacuum pressure of <0.1 mTorr and a temperature of 300 °C. The refractive index of the high-index dielectric layer Si₃N₄ (Si rich) was $n = 2.60$. The low-refractive index dielectric layer was SiO₂ ($n = 1.46$). The thicknesses of these layers were 66 and 110 nm, respectively. There were fourteen layers in total. The thickness of the top SiO₂ layer was approximately 450 nm. The silver nanowires, with diameters of 120 nm, were purchased from Nanjing XFNANO Materials Tech Co., Ltd., China. The silver nanowires were deposited on the dielectric multilayer and then the top surface of the multilayer was exposed to deionised water ($n = 1.33$) as the surrounding medium.

Experimental setup

A laser beam with a wavelength of 640 nm was expanded and collimated by a lens array and then directed onto the SLM (PLUTO, HOLOEYE Photonics AG, Germany) by a beam splitter. A computer-generated hologram (phase mask, such as Figure 1(b), Figure 3 (b) and (d), and Figure 4 (b), (d), and (f)) was used to address the SLM, after which the reflected laser beam was encoded with the designed spatial phase distribution and then focused onto the silver nanowire with objective-1 (5× and N.A. = 0.1 for Figure 2 and Supplementary Figures 3 and 7; 20× and N.A. = 0.5 for Figure 3 and Supplementary Figure 4; and 20× and N.A. = 0.3 for Figure 4 and Supplementary Figure 6). Simultaneously, the optical phase function of a lens was loaded on the SLM to represent a convex lens. The focal length of this lens can be tuned *via* its programming to ensure that it can be confocal with objective-1. The hologram (or the designed spatial phase distribution) can be projected onto the front focal plane of objective-1 where the silver nanowire is located. The leakage radiation of the excited BSWs was collected by objective-2 (100× and N.A. = 1.49) and then imaged by a tube lens onto two cameras (one each for the front and back focal plane images).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by MOST (2013CBA01703 and 2016YFA0200601), NSFC (61427818 and 11374286), and the Science and Technological Fund of Anhui Province for Outstanding Youth (1608085J02). This work was also supported by grants from the National Institute of Health (GM107986, EB006521, EB018959, and OD019975). This work was partially conducted at the University of Science and Technology of China's Center for Micro and Nanoscale Research and Fabrication. We thank Xiaolei Wen, Linjun Wang, and Yu Wei for their help with the micro/nano fabrication steps.

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Figure 1. Schematic illustration of the experiment

(a) Experimental setup. SLM refers to the spatial light modulator. (b) One example of a hologram loaded on the SLM. (c) Sample configuration. There were fourteen layers on the glass substrate; the thicknesses of SiO_2 and Si_3N_4 were 66 and 110 nm, respectively. The top SiO_2 layer had a thickness of 450 nm. The medium above the multilayer was deionised water. (d) Scanning electron microscopy of the silver nanowire, which had a diameter of approximately 120 nm. Two charge-coupled device cameras were used to image the front and back focal plane of objective-2 (100 $\times$ and N.A. = 1.49).

Figure 2. BSWs excited by the Gaussian beam

Panels (a), (c), (e), and (g) are white light images of Ag nanowires placed on a dielectric multilayer. The inset graph in panel (a) shows the focal spot of the Gaussian beam for a region without a nanowire, which is then projected onto the Ag nanowire. The boxes with the dashed lines indicate the position of the Ag nanowire onto which the Gaussian beam was focused. The Ag nanowires in panels (a) and (c) are straight, and those in panels (e) and (g) are curved. The corresponding LRM images presented in panels (b), (d), (f) and (h) show the propagation of the excited BSWs. Panel (i) illustrates the excitation of a BSW with a Gaussian beam focused onto a straight Ag nanowire, while panel (j) illustrates the simultaneous excitation and focusing of a BSW by a curved Ag nanowire. This illustration is

based on Huygens 'Principle. The scale bar in panel (a) is also applicable for the images in panels (b)–(h).

Figure 3. Tuning the propagation direction of the BSW

(a) White light image of a straight Ag nanowire on a dielectric multilayer. Panels (b) and (d) show the hologram loaded on the SLM to shape the incident laser beam. In these grayscale images, black represents large phase values and white represents small phase values. The phase change along the vertical direction is reversed in panels (b) and (d). The corresponding LRM images presented in panels (c) and (e) show the deflection of the BSW. The red line represents the position of the Ag nanowire, and the dashed line with the arrowhead indicates the direction perpendicular to the Ag nanowire. Panel (f) illustrates the deflection of the BSW. Here, the phase decreases from position P1 to position P3 along the Ag nanowire, resulting in an upwards deflection. This illustration is based on Huygens' Principle. θ represents the deflection angle of the BSW, which is -14° for (c) and -11° for (e). The scale bar in panel (a) is also applicable for the images in panels (c) and (e).

Figure 4. Tuning the width, length, and position of the BSW needle

(a) White light image of a straight Ag nanowire on a dielectric multilayer. Panels (b), (d), and (f) show the holograms loaded on the SLM to shape the incident laser beam with different parameters (n and q). In these grayscale images black represents large phase values and white represents small phase values. Panels (c), (e), and (g) show the corresponding LRM images of the excited BSW. The inset graphs in panels (c), (e), and (g) show the focal spot projected onto the Ag nanowire. Here, a smaller q value results in a short, narrow BSW needle. A non-zero value of n will induce a donut-shaped focal spot (inset graph in panel (g)). Panels (h) and (i) illustrate the formation of the BSW needle resulting from the interference between two deflected BSWs. This illustration is based on Huygens' Principle. The scale bar in panel (a) is also applicable for the images in panels (c), (e), and (g).