Realization of subwavelength guiding utilizing coupled wedge plasmon polaritons in splitted groove waveguides

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Abstract: A detailed numerical study of propagation characteristics of a coupled wedge plasmon polariton (CWPP) in splitted groove waveguide (SGW) formed with two metal wedges is performed by using the finite element method (FEM). It is shown that the SGW structure could confine CWPP modes tightly to the nano-gap region between the wedge tips, operating in a much broad bandwidth. The effect of the glass substrate, wedge roundness, gap width, groove wedge angle, and groove depth are also investigated. Particularly, our SGWs are found to be quite robust against groove depth reduction, which could be beneficial to minimize the waveguide structure dimensions. Feasibility of using such SGWs for the design of efficient subwavelength plasmonic elements is also discussed on the nanoscale whispering gallery resonators as an example.

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References and links

Surface plasmon polariton (SPP) is a fundamental electromagnetic excitation which may exist at the interface between metal and dielectric, with the fields decaying exponentially away from its maximum at the interface [1]. This inherently implies that SPPs can be laterally confined below the diffraction limit, and thus used as signal carriers to transport information in subwavelength waveguides [2]. A key issue in designing plasmonic waveguide geometries is to achieve a balance between modal confinement and propagation length [3]. Meanwhile, the convenience for technical realization should also be taken into account. Over the years, various plasmonic waveguide structures have been prototyped, including metallic stripes in symmetric [4,5] and asymmetric [6] environments, SPP band-gap structures [7], metallic nanoparticle chains [8], metal-insulator-metal (MIM) gap structures [9–11], dielectric-loaded SPP waveguides [12], V-shaped metal grooves [13], and A-shaped metal wedges [14], etc.

Among aforementioned plasmonic waveguides, V-grooves engraved in a thick metal film supporting channel plasmon polaritons (CPPs) have been demonstrated to show strong lateral confinement of the SPP fields at the bottom of grooves, simultaneously with low propagation losses at telecommunication wavelengths [13]. Furthermore, based on such kind of V-groove waveguide (VGW) structure, plasmonic functional devices such as ring resonators, Mach-Zehnder interferometers, and add-drop multiplexers, have been successfully realized [15, 16]. In contrast to the extreme plasmon confinement in narrow insulator films buried inside metal [17], VGW with a finite groove depth always involve electromagnetic fields extending significantly away from the groove bottom upon increasing the operating wavelength, and consequently producing a substantial degree of cross talk between neighboring waveguides, which thus limits the integration level and operation bandwidth of plasmonic circuits [18].

To improve the integration density of circuits, MIM gap structures have been attracting a great deal of attention due to its strong modal confinement. For example, Tanaka et al. simulated a SPP gap waveguide (SPGW) composed of a narrow gap region sitting in a wide gap region between two metallic plates, and showed that optical circuits based on SPGW could perform guiding, branching, and bending functions of optical waves in the nanometric device [9]. Liu et al. also proposed a “free-standing” MIM SPP waveguide formed by etching a small trench through a metallic thin film on a silica substrate and followed by coating an upper polymer cladding to construct a symmetric environment [11]. Note that in the previous studies on MIM gap SPP waveguides only rectangular gap structures are considered, in
which the two side-walls of the narrow gap are always assumed to be parallel and all the four corners are 90 degrees. However, from the point of view of experimental fabrication, it is difficult to introduce such an ideal rectangular gap into a metal film (usually the gap has a wider width on top) [19]. Then, a question is emerging naturally – what is the effect of a trapezoid shaped gap on the fundamental properties of MIM gap SPP waveguides?

In general, when a trapezoid shaped gap instead of a rectangular gap is introduced into a metal film, the formed structure - a splitted groove waveguide (SGW) can support highly confined coupled wedge plasmon polariton (CWPP) modes due to its reduced symmetry, which will be demonstrated later in the text. Actually, the dependencies of the fundamental CWPP modes on wedge angle, nano-gap width, and radius of curvature of the rounded tips have been investigated by Pile et al. in a geometry composed of a twin two-fold symmetric metal wedge with a nano-gap [20, 21]. Very recently, Manjavacas et al. suggested a structure consisting of parallel metallic nanowires for highly confining plasmon modes to the gap region defined by two neighboring wires, and thus allowing extremely compact plasmonic circuits in three-dimensional spaces [22]. As compared with the aforementioned coupled-SPP waveguides [20–22], the proposed SGW structure is much easier to fabricate.

Therefore, the main purpose of this work is to investigate the properties of the fundamental CWPP mode guided by sub-wavelength SGW structures at near-infrared-wavelengths. The effect of glass substrate, wedge roundness, groove depth and wedge angle (including the asymmetric case of two wedges with different angles) is determined and investigated through numerical calculations. SGW structures are found to be quite robust against geometrical variations, which could be beneficial to easily fabricate, and particularly, to minimize the waveguide structure dimensions. Feasibility of using such SGWs for the design of efficient subwavelength plasmonic elements is also discussed on an example of the nanoscale whispering gallery resonator (WGR). Compared to the case of the WGR using conventional VGW in Ref. 23, it is shown that very slight operation wavelength shift can be obtained in the ring resonator based on SGWs due to the negligible cross talk effect over the resonator disk.

2. The fundamental properties of CWPP modes in SGWs

Throughout this paper, we use the commercial FEM software package COMSOL Multiphysics [24] to evaluate the performances of the proposed waveguide structures. The complex effective index $N_{eff}$ is obtained from the mode analysis solver of COMSOL. The propagation wave vector $\beta$ and propagation length $L_{prop}$ are thus defined as follows:

$$\beta = \text{Re}(N_{eff}) \cdot k_0$$

and

$$L_{prop} = \frac{1}{2 \text{Im}(N_{eff}) \cdot k_0},$$

where $k_0$ is the wave vector in free space. In the calculations, the metal that constitutes the waveguides is gold with its dielectric constants described by a Drude-Lorentz model [25]. To avoid any nonphysical situations, all the sharp corners of the considered waveguide structures in this paper are rounded, and the maximum length of the triangular meshes is set to be less than 5 nm along rounded corners or at the metal-air interfaces.

Figure 1(a) schematically shows the lateral cross section (perpendicular to the direction of mode guiding) of the considered SGW structure, where $d$ is the groove depth (metal film thickness), $g$ is the gap width, and $\theta_1$, $\theta_2$ are two wedge angles. Obviously, the aforementioned rectangular gap MIM structure is a special case of the considered SGW structure with $\theta_1 = \theta_2 = 90^\circ$. The SGW structure is assumed to be surrounded by air (later we will demonstrate the effect of a higher refractive index substrate). Such a kind of freestanding SGW structure is possible to be fabricated experimentally by first milling a trapezoid shaped gap in a thin metal film supported on a silica substrate, and then using hydrofluoric to etch away a small part of silica substrate around the gap.
In order to check the validity of the code used in this paper, we first calculate the dispersion relation, propagation length, and field distributions for a conventional VGW with the same geometrical parameters as those given in ref [18], i.e., $d = 1.172 \, \mu m$, $\theta_1 = \theta_2 = 77.5^\circ$, and the corners are rounded with a 10 nm-radius curvature. The numerical results for the conventional VGW are shown in Fig. 2 (orange line). Here we focus on the fundamental CPP mode. It is seen from Fig. 2(a) that as the wavelength increases the CPP mode line gradually approaches the SPP dispersion curve, and at $\lambda = 1.44 \, \mu m$ (cut-off wavelength) it crosses the dispersion line of SPP mode on a flat gold/air surface (SPP\textsubscript{gold-air}), which is found to agree very well with the numerical results reported in Ref [18].

Fig. 2. (Color online) Dispersion relations (a) and propagation lengths (b) for the fundamental guiding modes of a conventional VGW (orange) and SGWs having three different gaps $g = 50$ nm (red), 100 nm (green) and 200 nm (blue). For both waveguide structures, the groove depth $d = 1.172 \, \mu m$ and the wedge angles $\theta_1 = \theta_2 = 77.5^\circ$. The dash-dotted line in (a) indicates the SPP dispersion curve on a flat gold/air interface.

Geometrically, the present SGW structure can be viewed as a truncated VGW with a finite groove depth [Fig. 1(b)], where the planar part below the groove is cut away, followed by separating two groove side walls with a small gap. For the purpose of a meaningful comparison the geometrical parameters of SGWs are set to be the same as those in the conventional VGW. The dispersion characteristics of SGWs with different gap widths $g = 50$ nm, 100 nm, and 200 nm are also shown in Fig. 2(a). Similar to the behavior of the fundamental CPP mode line of the VGW, the dispersion line of fundamental CWPP mode supported on SGWs also gradually approaches the SPP\textsubscript{gold-air} dispersion line as the wavelength increases. It is worth noting that similar to the rectangular gap structures the proposed SGW structures do not exhibit cutoff for fundamental guiding modes [26], which means that in the proposed SGW structures a much broader operation bandwidth can be achieved than in conventional VGW.

Meanwhile, Fig. 2(b) shows the propagation length as a function of wavelength for the conventional VGWs and SGWs with different gap widths. As mentioned in the introduction, there is a trade-off between mode confinement and propagation length, and in general, modes with shorter wavelengths provide better modal field confinement, but simultaneously make more modal energy absorbed by metal, i.e., exhibit more propagation losses. This is verified in Fig. 2(b) in which the propagation length increases with increasing the wavelength in each case. Comparing the propagation lengths of CWPP modes of the SGWs with different gap
It is seen that the guiding mode could propagate a longer distance for a larger gap width. In another word, SGWs with a smaller gap width could provide a better confinement for the guiding mode.

To visualize the above features, the modal shape of the fundamental CPP mode and CWPP mode for different exciting wavelengths are shown in Fig. 3. The time averaged electric fields were plotted in a contour scheme for clear vision. In each case, two exciting wavelengths located in the single-mode regime are selected. It is seen that for the conventional VGW, at $\lambda = 1.0 \, \mu m$ the CPP fundamental mode is hybridized with the modes running along the edges at both sides of the groove, though most of the fields are still confined by the groove sides [Fig. 3(a)]. The modal field is further expelled out of the groove when the wavelength is tuned to $\lambda = 1.4 \, \mu m$ (close to the cut-off), and is no longer guided at the groove bottom but rather at groove edges [Fig. 3(b)], in agreement with the results reported in Ref [18]. However, the modal field distribution becomes quite different for the SGWs for which the fundamental CWPP mode is almost completely confined within the nano-gap region between two metal wedge tips at an exciting wavelength $\lambda = 1.4 \, \mu m$ [see Fig. 3(c)]. As the wavelength is further increased, the modal field mainly begins to extend towards the top opening of the SGW [Fig. 3(d)]. In the case of the SGW with a gap width of 100 nm, similar situations are observed for the exciting wavelengths of $1.4 \, \mu m$ and $3.0 \, \mu m$ [Fig. 3(e) and 3(f)]. When the gap width becomes larger, it is also clear to see that the confinement level of the modal field is weakened as the modal area becomes larger [Fig. 3(c) and 3(e)].

Fig. 3. (Color online) Modal field distributions for the conventional VGWs at exciting wavelengths $\lambda = 1.0 \, \mu m$ (a) and $1.4 \, \mu m$ (b), and for SGWs at $\lambda = 1.4 \, \mu m$ (c) and $3.0 \, \mu m$ (d) with $g = 50$ nm, at $\lambda = 1.4 \, \mu m$ (e) and $3.0 \, \mu m$ (f) with $g = 100$ nm. All field panels have a lateral size of $1.55 \, \mu m \times 2 \, \mu m$. 

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Additionally, larger gap width even makes the modal field reach the top opening of the groove at a longer exciting wavelength [Fig. 3(f)].

3. The effects of the roundness of the sharp corner and substrate on the fundamental CWPP modes

![Dispersion relations for SGWs with three different curvature radiuses](image1)

Fig. 4. (Colour online) (a) Dispersion relations for SGWs with three different curvature radiuses $r = 10$ nm (red, hollow circle), 50 nm (dark yellow line) and 100 nm (blue, triangle) at the corners. The dash-dotted line represents SPP curve on a gold/air interfaces; (b) and (c) Modal field distributions for SGWs with curvature radiuses $r = 50$ nm (b) and $r = 100$ nm (c) at exciting wavelength $\lambda = 1.4 \mu m$. All field panels have a lateral size of $1.55 \mu m \times 2 \mu m$.

In the previously presented simulations, we only considered that the corners in SGW structures are rounded with a 10 nm-radius curvature. Since the edges of the splitted grooves might have a larger radius of curvature in the experiments, the dispersion curves and field distributions of the fundamental CWPP modes are recalculated for the SGWs ($d = 1.172 \mu m$, $\theta_1 = \theta_2 = 77.5^\circ$, and $g = 50$ nm) with larger radiuses of curvatures $r = 50$ nm and 100 nm to demonstrate the effect of the roundness of the sharp corner. Recently, groove wedges with the radius of curvature less than 80 nm have been experimentally realized [27], therefore our discussion for those three typical radius values have already covered the realistic situation. Note that during the variation of roundness of sharp corners the narrowest distance between two wedges is forced to keep a constant value of $g = 50$ nm here. For the purpose of direct comparison, the case of 10 nm-radius curvature is again plotted here. It is clearly seen that when the radius of curvature increases from 10 nm to 100 nm only at visible range (below the wavelength of ~800 nm) a tiny shift at visible range occurs to the fundamental CWPP mode dispersion curve [Fig. 4(a)]. By further comparing the field distributions at an exciting wavelength $\lambda = 1.4 \mu m$ for 50 nm and 100 nm-radius curvatures [Fig. 4(b) and (c)] with that for 10 nm-radius curvature [Fig. 3(c)], it is also found that the fundamental CWPP mode almost keeps constant modal shape for different curvature radius, except that the maximum fields move upward slightly along the groove side walls due to the geometrical ascent of the narrowest gap position. This implies that the roundness of the sharp corner does not alter the performance of the SGW waveguides in the near infrared range. In another word, the tolerance on the roundness of the sharp corner makes the experimental realization more easily. In the following calculations all the sharp corners are still assumed to be rounded with a 10 nm-radius curvature.
Now, let us consider a situation that a SGW structure is sustained on a dielectric substrate (glass, \(n = 1.5\)). Obviously, in this case of asymmetric dielectric environment the dispersion line of SPP mode on a flat gold/glass surface (SPP\(_{\text{gold-glass}}\)) should be taken into account. As seen from Fig. 5, the dispersion curve of fundamental CWPP mode for the SGW structure \((d = 1.172 \, \mu m, \theta_1 = \theta_2 = 77.5^\circ, \text{and } g = 50 \, \text{nm})\) crosses the SPP\(_{\text{gold-glass}}\) dispersion line at \(\lambda = 0.96 \, \mu m\) (cut-off wavelength). This implies that the SGW structure with a substrate significantly shorten the operation bandwidth of the fundamental CWPP mode. One of the ways to extend the operation range is to decrease the wedge angles. Also shown in Fig. 5 is the fundamental CWPP mode dispersion curve for a SGW \((d = 1.172 \, \mu m \text{ and } g = 50 \, \text{nm})\) with wedge angles \(\theta_1 = \theta_2 = 52.5^\circ\). In such smaller wedge angles, the fundamental CWPP mode cut-off wavelength is indeed extended to \(\sim 1.3 \, \mu m\). However, the \(x\)-directional size of the SGW structure is much enlarged simultaneously, which is a drawback for minimizing the waveguide lateral size. That is the reason why a freestanding SGW structure should be expected here.

4. Dependence on wedge angles

In this section, we turn to discuss the effect of the wedge angle on propagation characteristics of the SGW. Initially, the two wedge angles \(\theta_1\) and \(\theta_2\) are restricted to be varied equally \((\theta_1 = \theta_2)\). Figure 6(a) shows the fundamental modal effective index and propagation length as functions of the wedge angle for the SGWs with a gap width \(g = 50 \, \text{nm}\) and a groove depth \(d = 1.172 \, \mu m\) at an exciting wavelength \(\lambda = 1.4 \, \mu m\). It is predicted that upon decreasing both \(\theta_1\) and \(\theta_2\), the effective index (the propagation length) first decreases (increases), until it reaches a minimum (maximum) value of \(N_{\text{eff}} = 1.2\) \((L_{\text{prop}} = 13 \, \mu m)\) at \(\theta_1 = \theta_2 = 72^\circ\). With a further decrease in the wedge angles, the modal effective index (the propagation length) increases (decreases). Note that the case of \(\theta_1 = \theta_2 = 90^\circ\) corresponds to the MIM structure with a rectangular gap studied before [10], of which its modal field is confined within the gap region and distributed symmetrically along the horizontal mirror line [Fig. 6(b)]. As mentioned above, when the wedge angle deviates from 90\(^\circ\), i.e., a trapezoid shaped gap instead of rectangular gap is formed in the MIM structure, the horizontal mirror symmetry is broken. For a direct comparison, we also plot the mode profiles for SGWs with two slightly smaller wedge angles 88\(^\circ\) and 86\(^\circ\). It is seen that most of the modal field now begins to be confined more and more within the waveguide bottom part of the gap region with decreasing the wedge angles [Fig. 6(c) and 6(d)]. On the other hand, when the wedge angle becomes quite small, the SGW could be viewed as a bowtie configuration waveguide composed of twin metal wedges having a two-fold symmetry [20, 21]. As an example, the fundamental CWPP mode for \(\theta_1 = \theta_2 = 4^\circ\) now looks like a field superimposed by two wedge plasmons, which is bounded at both wedges and in the gap between wedges [Fig. 6(e)].
As a matter of fact, the two wedge angles $\theta_1$ and $\theta_2$ could be varied independently in the experimental process. For clarity, here the left wedge angle $\theta_1$ is assumed to be fixed (90°, 77.5° and 65°), and only the right wedge angle $\theta_2$ is continuously varied. Again, the fundamental modal effective index and propagation length are plotted in Fig. 7(a) against the right wedge angle $\theta_2$ for the SGWs ($d = 1.172 \mu m$ and $g = 50$ nm) at an exciting wavelength $\lambda = 1.4 \mu m$. It is seen that the effective index and propagation length curves for the asymmetric case ($\theta_1 \neq \theta_2$) show the similar trends as those for the symmetric structure ($\theta_1 = \theta_2$). It is interesting that all three cases exhibit almost the same dependence upon the variation of the right wedge angle $\theta_2$ when $\theta_2$ is smaller than 50°. From the modal field distributions shown in Fig. 7(b) and 7(c), the fundamental CWPP modes of such asymmetric SGWs are still found to be well confined within the gap region.

5. Robustness against groove depth variations

Previous studies have showed that for conventional VGW the groove depth plays a key role in the propagation characteristics and modal shapes [28]. Generally, a deeper V-groove means broader operation bandwidth and better modal confinement. However, in this way the lateral dimension of the VGW is increased, which is negative to a compact integration of plasmonic circuits. In the present SGWs, the fundamental CWPP mode is exclusively confined within the nano-gap region between the metal wedge tips. Thus SGWs could provide us a new avenue to further minimize the waveguide dimensions by reducing the groove depth while simultaneously maintaining good field confinement for guiding mode.
Fig. 8. (Color online) (a) The effective indexes (red symbol lines) and propagation lengths (blue symbol lines) as functions of the groove depth $d$ at a wavelength $\lambda = 1.4 \, \mu m$ for conventional VGW (square), and $g = 50$ nm SGWs with two different wedge angles: $\theta_1 = \theta_2 = 77.5^\circ$ (circle) and $65^\circ$ (triangle). The red dotted line indicates the effective index of a SPP on a flat metal/air interface at $\lambda = 1.4 \, \mu m$; (b) The variation of the cutoff wavelengths of the second-order guiding mode with the groove depth $d$ for $\theta_1 = \theta_2 = 77.5^\circ$ (circle) and $65^\circ$ (triangle) SGW structures (circle and triangle).

Figure 8(a) shows the dependences of the effective index and propagation length on the groove depth at the exciting wavelength $\lambda = 1.4 \, \mu m$ for the conventional VGW and the SGWs with two different groove wedge angles ($\theta_1 = \theta_2 = 65^\circ$ and $77.5^\circ$). It is seen that as the metal film becomes thinner the fundamental CPP modal effective index decreases quickly and crosses the flat SPP modal effective index line at the groove depth of $\sim 1.1 \, \mu m$. A similar decrease tendency is observed for the propagation length of the fundamental CPP mode [28]. For the SGWs presented here, however, it is seen that both the effective index and propagation length are almost independent of the groove depth when $d$ is larger than $\sim 0.7 \, \mu m$, which means the $y$-axis dimension (i.e., the groove depth) of the SGW could be reduced considerably, for example, to $d = 0.7 \, \mu m$, with strong mode confinement and relatively large propagation length remained. When the groove depth becomes smaller than $\sim 0.7 \, \mu m$, wedge plasmons at the top opening begin to take part in the mode coupling, in addition to the coupling between two wedge plasmons at the bottom opening of the SGW. This explains why the effective index (propagation length) begins to increase (decrease) with decreasing the groove depth of the SGW for $d < 0.7 \, \mu m$ [Fig. 8(a)].

Figure 8(b) shows that the cut-off wavelengths of the second mode in SGWs are also dependent on the groove depth. Upon decreasing the groove depth, the cut-off wavelengths of the second-order modes monotonically decreases, which can be explained by the deeper coupling between the bottom groove wedges and top ones. Therefore, a broad single mode operation bandwidth ($\lambda > 0.9 \, \mu m$) can be achieved when the groove depth of SGW ($\theta_1 = \theta_2 = 77.5^\circ$) is decreased to $0.5 \, \mu m$ for example. Such kind of feature can be exploited to make the SGWs operate in a single mode in a wide region of wavelengths by decreasing the groove depth.

6. Whispering gallery resonator constructed from SGWs

Recently, Vesseur et al. have reported a successful realization of plasmonic WGRs based on the conventional VGW structure at optical wavelength region [23]. In that work, due to the relative large modal size of the conventional CPP mode, the coupling of the CPP mode across the disk leads to a significant blue-shift of the resonance wavelengths compared to the values obtained from the ring resonance condition.

In this section, to illustrate the feasibility and advantages of using the SGW structure for design of subwavelength plasmonic elements, a nano-scale WGR operating at the telecommunication wavelength region is presented. In the simulations, the SGW structure has a gap width of $g = 50$ nm, a groove depth of $d = 600$ nm, and wedge angles $\theta_1 = \theta_2 = 77.5^\circ$ and the radius of the ring resonator is $R = 0.414 \, \mu m$ [Fig. 9(a) inset]. The resonant wave
vectors $\beta$ could be easily calculated according to the ring resonance condition $\beta = mlR$, where $m$ is the azimuthal momentum number [22, 23]. Therefore, resonances with $m = 1, 2,$ and $3$ for the fundamental CWPP mode at wavelengths of 2.96 $\mu$m, 1.55 $\mu$m, and 1.06 $\mu$m are predicted from those crossing points (ring resonance condition) between the vertical lines and the fundamental CWPP dispersion curve in Fig. 9(a). Note that the predicted values are valid only for those ideal ring resonators where modal fields are extremely confined within the waveguide, i.e., without any cross talk of the guiding mode in the annular waveguide. Thus, in our proposed ring resonators, a weakened coupling of the CWPP mode across the disk should be expected owing to its better modal confinement in the SGW structures.

To give a more clearly demonstration, we also performed eigenvalue analysis for the proposed ring resonator [29]. It is seen that the calculated wavelength eigenvalues [indicated by solid symbols in Fig. 9(a)] of 3.09 $\mu$m and 1.54 $\mu$m, and 1.10 $\mu$m for $m = 1, 2,$ and $3$ which agree quite well with the values predicted from the ring resonance condition (deviation < 4.5%). The cross-section field distributions of the ring resonator for $m = 1$ and 2 whispering-gallery modes are plotted in Fig. 9(b) and 9(c), which show the strong confinement nature intuitively. In addition, the modal field distributions are found to be almost the same as those shown in Fig. 3(c) except a slight distortion inside the groove region, which illustrates that the presented SGW structure could be an ideal candidate for subwavelength plasmonic elements.

Fig. 9. (Color online) (a) Relations between the fundamental CWPP dispersion (red) and whispering-gallery resonances in an annular SGW. The black dash-dotted line indicates the SPP dispersion curve on a flat metal/air interface. The vertical dashed lines (navy blue) indicate the locations of the resonant wave vectors according to the whispering-gallery resonance condition for different azimuthal momentum numbers $m = 1, 2,$ and $3$. The symbols on the vertical lines show the wavelength eigenvalues of the whispering-gallery modes calculated by FEM analysis. Inset: the top view (upper panel) and the medial cross section (bottom panel) of the proposed ring resonator. (b)-(c) The corresponding field (|E|) distribution for $m = 1$ (b) and $m = 2$ (c) whispering-gallery resonant modes along the medial cross section of the ring resonator. All field panels have a lateral size of 1.50 $\mu$m × 0.93 $\mu$m

5. Conclusion

We have numerically investigated the propagation characteristics of the supposed SGW as an optional prototype of the plasmonic waveguide structure. From the results shown above, our proposal has revealed broad operation bandwidth and good modal field confinement. We further discuss the effect of glass substrate and wedge angle roundness from the point of view of the experimental fabrication. The detailed dependence of the propagation characteristics on the geometric parameters, such as the gap width, wedge angle, and groove depth, has also been calculated, and we further demonstrate that the robustness against the groove depth should be a highlight of our SGW structure. For considering the prospective applications in plasmonic circuits, a nanoscale WGR operating at telecommunication wavelengths has also
been designed and numerically discussed. Very slight operation wavelength shift can be obtained in our designed ring resonator due to the negligible cross talk effect over the resonator disk, which further illustrates that our SGW structure could be a promising candidate for the subwavelength compact plasmonic circuits.

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