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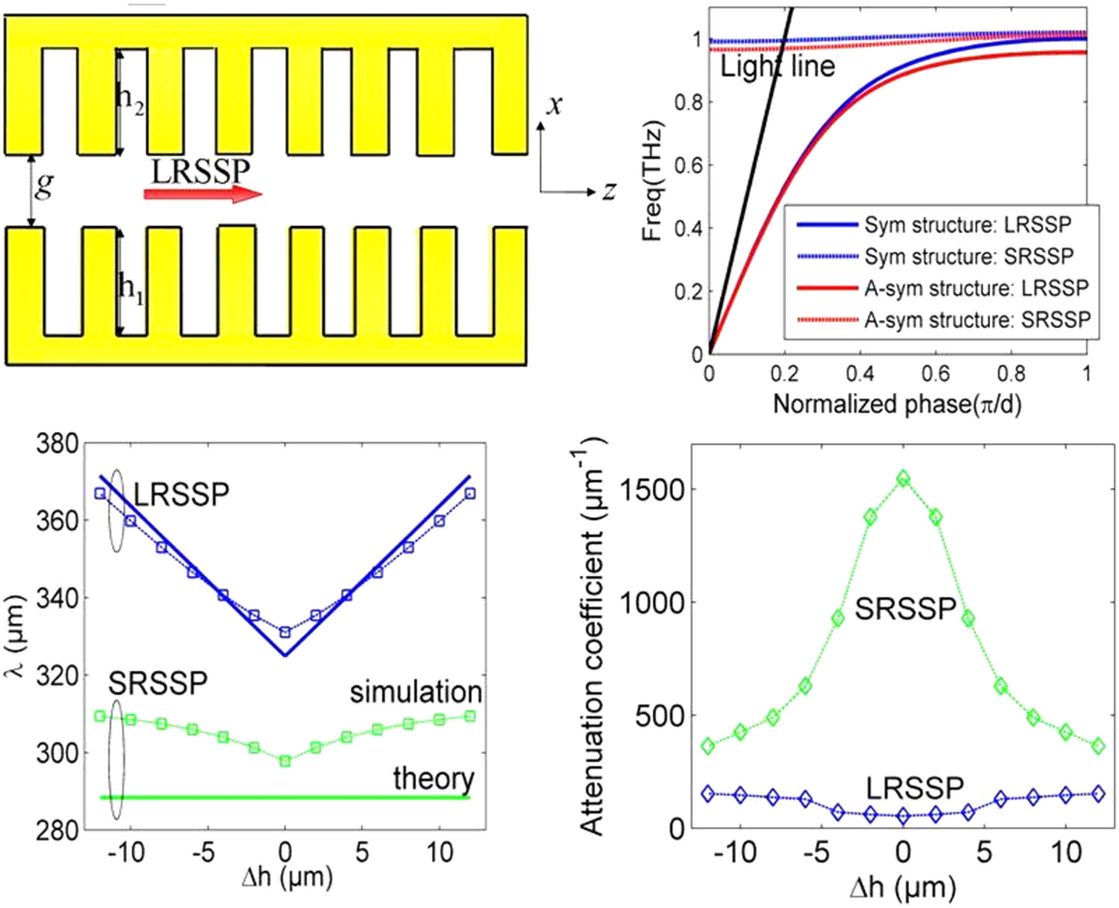

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Abstract: Spoof surface plasmons (SSP) on the corrugated metal surfaces have been widely studied over the past decade in both microwave and Terahertz (THz) band. Previous studies show that SSP mode on the metal grating suffers from high dissipative losses in high THz band especially near asymptotic frequency which may limit its real applications. The issue can be addressed by utilizing long-range SSP mode (LRSSP). LRSSP is a special low-loss symmetric propagating surface wave mode along double-layer corrugated metallic waveguides. In this paper, the asymmetric double metal gratings are proposed to support LRSSP which can significantly reduce the damping losses of the other short-range SSP mode (SRSSP) on the conventional doubly-corrugated metallic surfaces, thus enabling new possibilities to utilizing this SRSSP mode within long-range manner. According to our dispersion theory and the numerical calculations, the propagation loss of LRSSP is still lower than that of SRSSP within asymmetric regime, which demonstrates good tolerance to the asymmetry of the double-layer corrugated structure. However, its long-range propagation superiority of LRSSP vanishes gradually as the degree of asymmetry is enlarged. This work provides an alternative approach to increase the propagation length of SRSSP mode on the doubly-corrugated metallic surfaces and can open up new avenues to develop some novel LRSSP-based plasmonic devices such as waveguides, filters, sensors and active powerful radiation sources induced by energy beam below optical spectrum.

Index Terms: Spoof surface plasmons, long-range, asymmetric double metal gratings, dispersion, propagation loss, Terahertz applications.

1. Introduction

Surface plamon polaritons (SPP) is an optical excitation coupling mode which propagates along two different medium interfaces e.g., on the metal-dielectric [1]. Its intriguing properties such as the sub-wavelength confinement and strong local resonant effect have attracted widespread attentions in the society of modern optics and photonics [1]–[2]. Besides, SPP mode on the metal-dielectric interface have brought out many novel optical and physical phenomena and thus open up various applications such as sensing, imaging, sub-wavelength guiding, etc. However, SPP mode on the single propagating interface (Fig. 1(a)) usually induces high dissipative losses stem from the strong resonance into the metal. One effective way to reduce SPP attenuation is to use two dielectrics bound the upper and lower metal film or strip surface (Fig. 1(b)). As the metal film thickness decreases, the field of SPP mode on the single upper and lower interface can couple with each other, thus a new symmetric SPP mode occurs on the structure. This low loss symmetric SPP mode

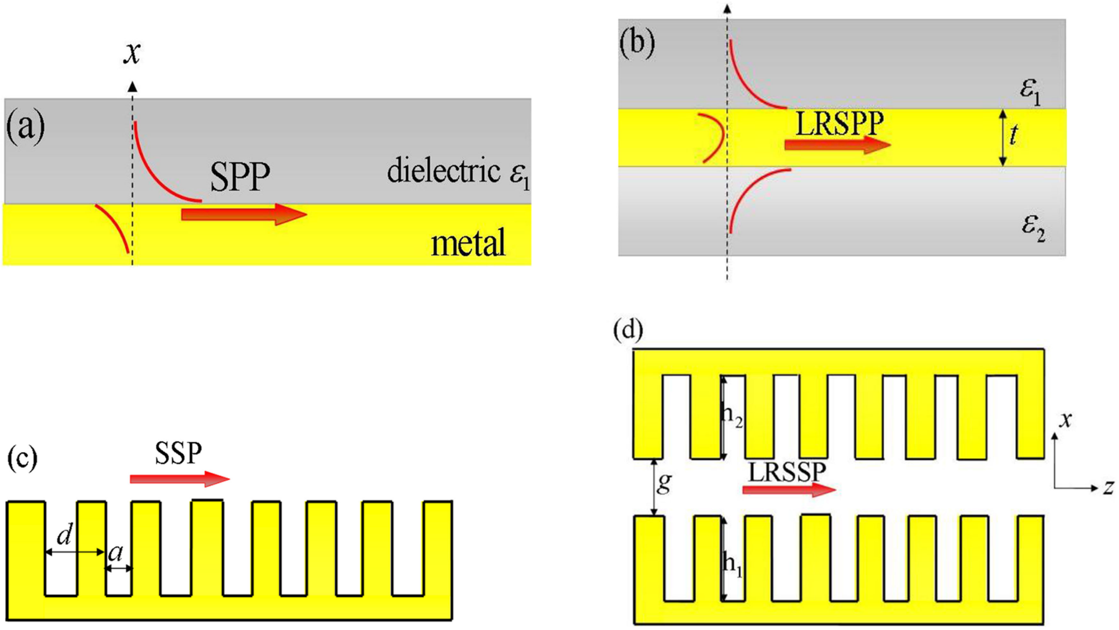

Fig. 1. (a) SPP mode on the single metal-dielectric (ε_1) interface. (b) Double layer metal-dielectric (ε_1 and ε_2) interface support long-range SPP (LRSPP) in optic band. Red curves show the transverse field distribution of SPP and LRSPP mode. (c) Spoof surface plasmons (SSP) mode on the single corrugated metal grating. (d) Double metal grating support long-range SSP (LRSSP) below optical spectrum. The different upper and lower metal grating groove depth h_2 and h_1 indicate the asymmetry of proposed structure.

on the double-layer metal-dielectric interfaces is termed as long-range SPP (LRSPP) [2]. LRSPP is well-established and widely studied in optical society and has found many practical applications thanks to its lower propagation loss compared with single interface [2]–[3].

In low frequency band such as Terahertz (THz), SPP is usually on the corrugated metal surface considering good field confinement which is known as spoof surface plasmons (SSP). The “spoof” plasmon mode considering fundamental perspectives and practical applications have aroused a great deal of attentions in the both THz and microwave society. The propagation characteristics of SSP can be tailored at will by changing parameter-dependency geometry topology and/or the ambient environment surrounding the corrugated surface. Besides, the researches on its excellent properties of SSP mode also lead to some novel phenomena and various potential applications have been widely proposed. For the detailed progresses and advancements in this field, one can refer to some recent review articles in the microwave [4]–[5] and THz [6]–[7] band, respectively.

Among various patterned structures, single corrugated metal grating (Fig. 1(c)) has been widely studied and proposed for many interesting applications from microwave to THz [8]–[13] owing to its simple implementations and easy fabrications. Damping losses of SSP mode can deteriorate the performance of every plamonic device and system both for passive and active ones especially in high frequency band [9]–[10], [14]–[15]. This issue can be addressed by using low-loss SSP mode on the doubly-corrugated metal surfaces [14]–[16]. Thus, long-range SSP mode (LRSSP) is specifically proposed on the double layer corrugated metal structure [16]. LRSSP is the low-loss propagating SSP mode similar to the LRSPP in optical band which is propagating along double layer metal-dielectric interfaces (Fig. 1(b) and (d)). The other anti-symmetric lossy SSP mode is termed as short-range SSP (SRSSP). Double metal gratings have been proposed for a series of passive devices such as mode converter and modulators [17]–[19], sensors [20]–[22], waveguides, filters [23]–[26] and also some novel active devices such as THz laser or beam emitters [27]–[29]. For these demonstrated studies on double metal grating, the metal is mostly assumed as perfect electric conductor and the damping losses are ignored. The propagation losses on the structure can be noticeable especially in high THz band which can even approaching 3dB thus the conditions become critical for real-life applications [15], [20]–[22], [27]–[29]. Besides, the above mentioned studies are mainly on the strictly symmetric double-layer corrugated structure even for the staggered one [15], [30] (i.e., $\mathrm{h}_1 = \mathrm{h}_2$ in Fig. 1(d)). However, for practical applications, it is not always conveniently the same with each other between the upper and lower metal grating thus the asymmetry on the structure should be specifically considered and investigated. Additionally, the asymmetry can provide a new degree of freedom to tailor SSP mode on this kind of doubly-corrugated plasmonic platform [14]–[30].

Previously, the asymmetry is specifically talked about and investigated in other shaped structures such as "T"-shape [31] and "H"-shape [32] plasmonic waveguide. However, the dispersion theory of SSP mode are still lacking because of its complicated asymmetric conditions. SSP modes on the asymmetric doubly-corrugated metal surfaces with various parameters are studied both theoretically and numerically [33]. However, the fundamental dispersion expressions of LRSSP and SRSSP mode are uncovered analytically therein [33], which are vital for further applications. More importantly, the evolutions of LRSSP and SRSSP dispersion modes along with various asymmetries on the structure are not conducted so far. To this end, the asymmetric double metal gratings are here proposed to support LRSSP modes, which can break the strictly symmetric limitation of conventional structure [14]–[30]. Besides, the modal characteristics of both LRSSP and SRSSP mode with various asymmetric degrees are studied and analyzed in THz band both theoretically and numerically. It is shown that the propagation loss of SRSSP mode can be reduced largely within asymmetric regime which can open up new avenues to develop some SRSSP-based high-performance devices such as low-loss filters, sensors and enhanced radiation source in THz band.

2. Dispersion Theory

The proposed asymmetric double metal grating without transverse stagger is schematically illustrated in Fig. 1(d) on x-z plane. For the SSP mode along metal grating, its propagation characteristics are mainly determined by its groove depth [8]–[13]. Here, the asymmetry on the double metal gratings is indicated by the different lower and upper grating depth of h_1 and h_2, respectively. Other parameters of period d and groove width *a* are the same with each other. The gap size between the different metal grating surfaces is marked as *g*. SSP modes with transverse-magnetic (TM) polarization along z direction are well-studied in [15]–[16] with modal expansion calculations, in [17] with transfer matrix method and/or in [18]–[19] by a full-field analysis for 2-D and 3-D symmetric structure with $\mathrm{h}_1 = \mathrm{h}_2$ conditions. Besides, the analytical dispersion expressions can be obtained therein [15]–[19]. However, these dispersion theories and calculations cannot be directly applied to the asymmetric double metal gratings. Thus, to develop a suitable dispersion theory on the asymmetric double-layer corrugated structure still needs more efforts and works. Here, a simplified modal field expansion method is used to study the dispersion characteristics of SSP. The frequency of interest is in THz and the wavelength is usually much larger than lattice period. Thus, it's reasonable to only consider the fundamental mode fields in the groove regions. The initial point of *x* axis is on the gap center and the symmetry axis is defined along the gap center in Fig. 1(d). According to above assumptions, using the boundary conditions on the each groove bottom, the fields into lower and upper groove region can be obtained, respectively, i.e.,:

$$E_z^L = A \sin k \left(x + \frac{g}{2} + h_1 \right) e^{-j\beta_0 md} \tag{1}$$

$$E_z^U = B \sin k \left(x - \frac{g}{2} - h_2 \right) e^{-j\beta_0 md} \tag{2}$$

Where *A* and *B* are undetermined coefficients, *j* is imaginary unit, β_0 is propagation constant and *k* is wave vector in free space. The fields into groove regions are different as denoted by different "L" and "U" superscript in expressions which consider the different lower and upper groove depth of

h_1 and h_2, respectively. According to Maxwell's equations, the magnetic fields can also be readily obtained in each groove, i.e.,:

$$H_y^L = A\frac{k}{j\omega\mu}\cos k\left(x+\frac{g}{2}+h_1\right)e^{-j\beta_0 md} \tag{3}$$

$$H_y^U = B\frac{k}{j\omega\mu}\cos k\left(x-\frac{g}{2}-h_2\right)e^{-j\beta_0 md} \tag{4}$$

For the fields between asymmetric double metal gratings, the expressions are the same form with symmetric structure [15]–[16], that is:

$$E_z = \sum_{n=-\infty}^{\infty}[C_n \sinh k_n x + D_n \cosh k_n x]e^{-j\beta_n z} \tag{5}$$

$$H_y = \sum_{n=-\infty}^{\infty}\frac{-j\omega\varepsilon}{k_n}[C_n \cosh k_n x + D_n \sinh k_n x]e^{-j\beta_n z} \tag{6}$$

Where C_n and D_n are unknown indexes, $\beta_n = \beta_0 + 2n\pi/d$ is corresponding propagation wave vector of harmonic mode, $k^2{}_n = \beta^2{}_n - k^2 (n = 0, \pm1, \pm2, \pm3 \ldots)$. By matching boundary conditions on the upper and lower grating interface and the power flux conservation along y direction in one period is applied, the above unknown coefficients can be eliminated finally. Thus, the following equations can be used on the upper interface of x = g/2:

$$E_z^U\big|_{x=g/2} = E_z\big|_{x=g/2} \tag{7}$$

$$aH_y^U\big|_{x=g/2} = \int_{-a/2}^{a/2} H_y\big|_{x=g/2} \tag{8}$$

Also, the following equations are satisfied on the lower interface of x = –g/2, i.e.,:

$$E_z^L\big|_{x=-g/2} = E_z\big|_{x=-g/2} \tag{9}$$

$$aH_y^L\big|_{x=-g/2} = \int_{-a/2}^{a/2} H_y\big|_{x=-g/2} \tag{10}$$

By substituting the above electric and magnetic fields in each region of expressions from (1)-(6) into the equations of (7-10), the final dispersion expressions of SSP mode on the asymmetric structure can be obtained. These detailed calculations and the derivation progresses for the analytical dispersion expression of SSP mode are similar to our previous studies on the symmetric structure [29]. LRSSP mode dispersion expression on the asymmetric structure arises after tedious calculations, i.e.,:

$$\frac{\cot(kh_2)}{k} = \frac{a}{d}\sum_{n=-\infty}^{\infty}\frac{1}{k_n}\sin c^2\left(\frac{\beta_n}{2}a\right)\coth\left(\frac{k_n}{2}g\right) \tag{11}$$

And for SRSSP mode, the result is:

$$\frac{\cot(kh_1)}{k} = \frac{a}{d}\sum_{n=-\infty}^{\infty}\frac{1}{k_n}\sin c^2\left(\frac{\beta_n}{2}a\right)\tanh\left(\frac{k_n}{2}g\right) \tag{12}$$

3. Results and Discussions

The above derivation processes about SSP dispersion theory on the asymmetric structure have considered harmonic modes of SSP and the results can be degraded to conventional ones [15]–[19] if $h_1 = h_2$ is set. Here, the symmetric and anti-symmetric SSP modes are dependent on the different upper and lower groove depth according to the presented results. Thus, the

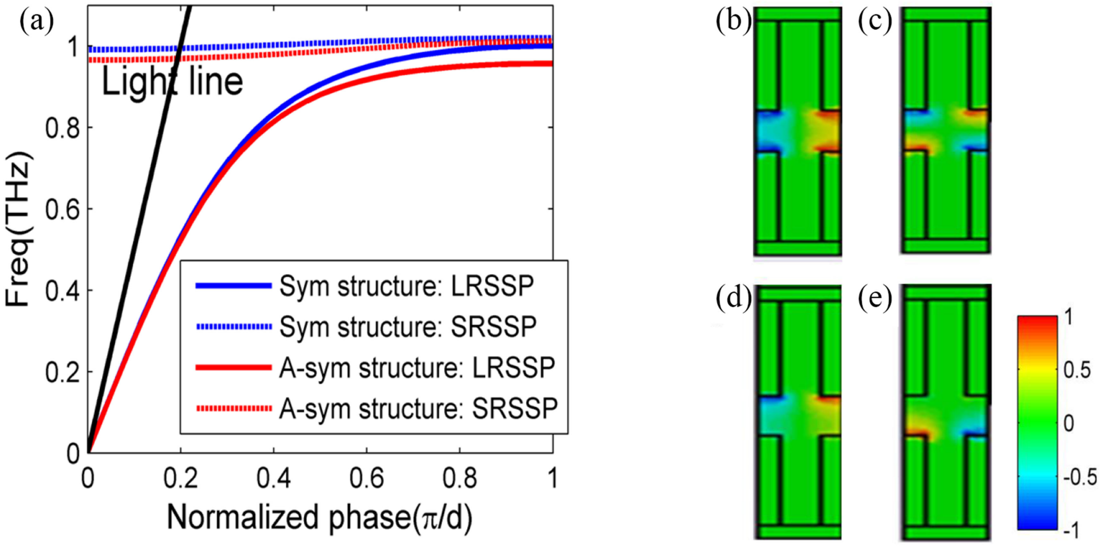

Fig. 2. (a) LRSSP (red solid line) and SRSSP (red dotted line) dispersion lines on the asymmetric double metal gratings. SSP modes on the conventional symmetric structure are also plotted for comparison as blue lines. The right panels are corresponding dominant fields for (b), (c) symmetric and (d), (e) asymmetric structure of LRSSP and SRSSP near asymptotic frequency in dispersion diagram, respectively. The black line is light line in free space.

propagation characteristic of symmetric and anti-symmetric SSP modes can be tuned on the asymmetric structure independently. It should be noted that the proposed modal expansion method uses a unified field expression between double metal grating surfaces thus is simple and fast compared with other derivation processes [17]–[19]. By solving above transcendental dispersion equations of (11) and (12) numerically and set $0<\beta_n<\pi/d$ we plot the fundamental symmetric and anti-symmetric dispersion mode shown as red solid and dotted line in Fig. 2(a), respectively. Considering the lower propagation losses of symmetric SSP mode on the symmetric structure [16], it is termed as long-range SSP (LRSSP) below. Also, the anti-SSP mode is termed as short-range SSP (SRSSP). The structural parameters in Fig. 1(d) are: $a/d = 0.5$, $d = 30\mu$m, $h_1 = 66\mu$m, $h_2 = 70\mu$m, $g = 30\mu$m. It has been demonstrated that LRSSP and SRSSP mode gradually overlap with each other as the increased frequency on the symmetric structure [16], [24].

Previous studies show that SSPs mode on the doubly-corrugated metal surfaces can be tuned by changing various parameters [15]. For the symmetric double metal grating, the asymptotical frequency of LRSSP and SRSSP mode usually overlaps with each other. Thus, it is hard to excite LRSSP and SRSSP mode on the conventional symmetric structure independently. For the proposed asymmetric double metal grating, it can be noted that the asymptotical frequency of LRSSP and SRSSP splits obviously. For comparison, LRSSP and SRSSP mode with conventional symmetric structure ($h_1 = h_2 = 66\mu$m) are also given as blue lines. The asymmetric structure demonstrates larger degree of freedom to manipulate SSP modes on the structure. The right upper (b), (c) and lower (d), (e) panels are the dominant transverse field profiles of symmetric and asymmetric structure both for LRSSP and SRSSP mode, respectively. The results are near asymptotic frequency in the dispersion diagram which is from numerical simulation based on finite integration method (FIM). From the field distributions, the standard symmetry of LRSSP and SRSSP mode is breaking for the asymmetric double metal grating structure. Besides, it seems that LRSSP mode energy mainly resides on the upper groove grating surface while SRSSP mode on the lower groove grating surface for the given asymmetric structure. For SPP mode on the asymmetric structure as shown in Fig. 1(b) with different bounded dielectric ε_1 and ε_2, where

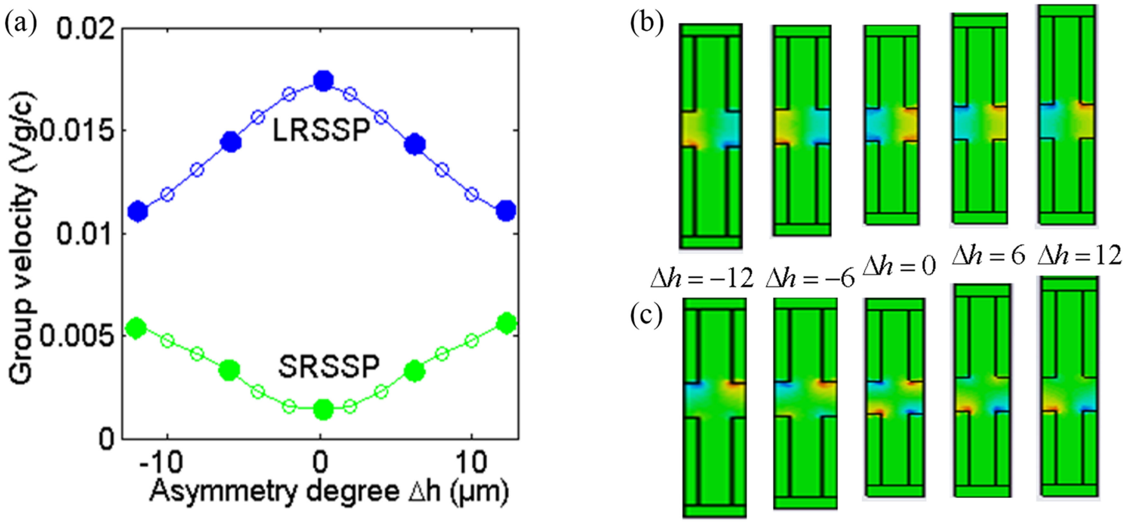

Fig. 3. (a) Group velocity variations of LRSSP and SRSSP mode along with the asymmetry degree Δh (h2-h1) on the proposed structure. (b) Right upper and (c) lower panels are the corresponding dominant field profiles of LRSSP and SRSSP mode which are indicated by the lighted point in curve with defined Δh = -12, -6, 0, 6, 12μm, orderly.

LRSPP mode evolves into the low-index cladding interface while SRSPP mode evolves into the high-index cladding interface [2].

Two separated corrugated metal surfaces create an efficient slow wave plasmonic waveguide which can be used as novel slow-light system [14], [23] and enhanced light-matter interaction system [27]–[29]. Here, the slow wave effect is specifically studied for LRSSP and SRSSP mode on the proposed asymmetric structure. Based on the presented dispersion theory, the group velocity of LRSSP and SRSSP mode can be calculated with various asymmetry degrees ($\Delta h = h_2$-h_1) as defined by $v_{\mathrm{g}} = \mathrm{d}f/\mathrm{d}\beta_{\mathrm{n}}$, f and β_{n} are frequency and propagation constant of SSP mode in the dispersion band. Fig. 3(a) shows how the group velocity of LRSSP and SRSSP mode evolves with various Δh. The group velocity of SRSSP mode increases slightly with the increased asymmetry degree while LRSSP decreases inversely. In view of normalized v_{g} with c (c is light velocity in free space), SRSSP mode demonstrates better slow light effect than LRSSP for large asymmetry. This novel property of SRSSP mode can be specifically utilized for some new applications such as efficient THz radiation source which based on the enhanced extremely slow light-matter interaction [29]. It is revealed that SRSSP mode can be totally stopped as group velocity v_{g} approaches zero as the minimum gap size of symmetric structure is around [16]. It can be concluded that this critical gap size can be enlarged on the proposed asymmetric structure according to our analysis. The transverse field contours of LRSSP and SRSSP mode with various asymmetry of Δh = -12, -6, 0, 6 and 12μm are given in the right upper and lower panels (Fig. 3(b) and (c)) for LRSSP and SRSSP mode, respectively. The corresponding Δh in the line is also indicated by its solid lighted point in Fig. 3(a). Symmetry and anti-symmetry property of LRSSP and SRSSP mode is obvious for symmetric one ($\Delta h = 0$) in the middle. For the asymmetric structure, the dominant symmetry of LRSSP field still can be seen with small asymmetry. However, field energy of LRSSP mode gradually evolves into the corrugated metal surface with larger depth as can be seen with right ones of $\Delta h > 0$ and left ones of $\Delta h < 0$. $\Delta h > 0$ indicate upper groove with is larger than the lower groove depth while is smaller for $\Delta h < 0$ but with the same initial value of groove depth of $h_1 = h_2 = 66\mu$m. For SRSSP mode, the anti-symmetry is broken obviously even with small asymmetry. Besides, its mode energy evolves into the corrugated metal surface with smaller depth. This implies that the mode field variation of SRSSP mode is more sensitive than LRSSP mode on the asymmetric structure.

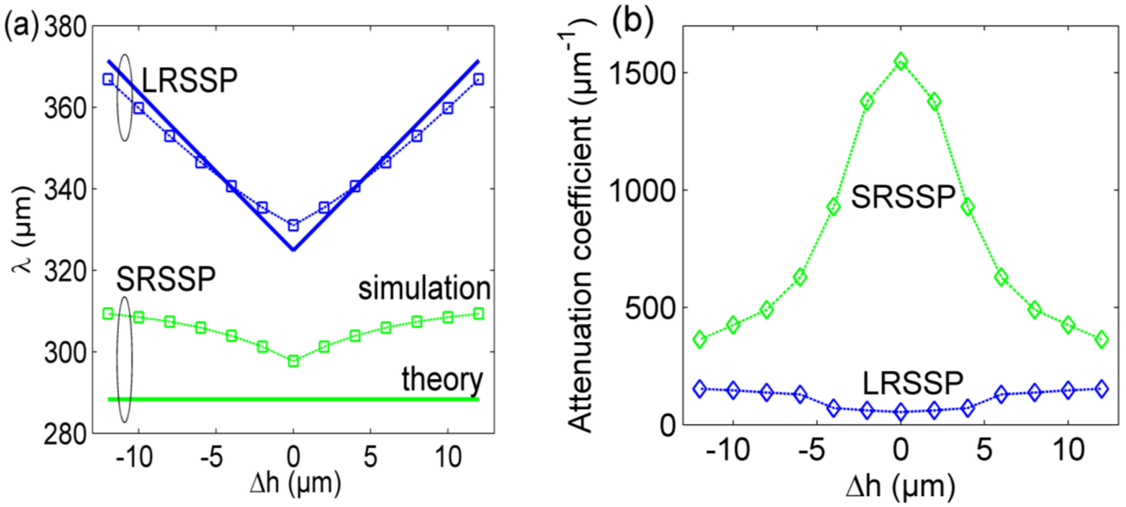

Fig. 4. (a) The modal wavelength evolution of LRSSP and SRSSP mode with asymmetry degree Δh. (b) Attenuation coefficient variation of LRSSP and SRSSP mode along with Δh. Other parameters are the same with Fig. 2.

Dispersion modal engineering of SSP mode is of great importance for the various applications on the double metal grating. Also, the propagation losses can determine the performance of every plasmonic device. The losses issue should be addressed especially in high frequency which is near asymptotic frequency. Here, the wavelength and damping losses change of LRSSP and SRSSP mode are presented with various asymmetries on the proposed structure. Fig. 4(a) illustrates the theoretical wavelength variation of LRSSP and SRSSP mode with Δh which is also verified by numerical simulation. There is a good agreement between theory and numerical simulation. SRSSP mode is almost unchanged with various asymmetries as the smaller groove depth is kept constant. This is accordant with the SRSSP modal evolution analysis in Fig. 3. The modal wavelength discrepancy between LRSSP and SRSSP mode enlarges with increased Δh. Propagation losses of SSP mode on the symmetric structure are studied in [14]–[16], [24] for real metal with limited conductivity. Symmetric SSP mode demonstrate much lower propagation loss than the other anti-symmetric SSP mode thus the symmetric SSP mode is dubbed as long-range SSP (LRSSP) mode [16]. Here, the propagation losses of LRSSP and SRSSP mode are specifically addresses for the asymmetric double metal grating. The attenuation coefficients of LRSSP and SRSSP mode with asymmetry is calculated and presented in Fig. 4(b). The real metal is copper and its conductivity of $\sigma = 5.99\times10^{7}\ \Omega^{-1}*\mathrm{m}^{-1}$ in THz regime is used [14]–[16]. Appling the Drude modal and using $\mathrm{Im}(\beta n) = \pi * f/(v_g * Q)$, the propagation losses of SSP mode can be obtained. f is eigen-frequency in the dispersion diagram and v_g is group velocity of SSP mode which has been studied in Fig. 3. Q is the quality-factor of asymmetric structure in a single unit cell. The calculated Q value is from FIM. It is shown that the propagation losses of LRSSP mode slightly increase with the asymmetry of structure. Inversely, the propagation losses of SRSSP decrease with Δh largely. This can be explained that LRSSP mode gradually resides into the grating surface with larger groove depth and the SSP mode suffers from larger damping losses accordingly [9], [15]. SRSSP mode occupies its own location in the dispersion band and can also find some novel applications though its losses are high on the conventional structure. Here, the propagation losses of LRSSP are significantly reduced on the proposed asymmetric structure. LRSSP mode is less sensitive to the asymmetry than SRSSP mode which still reveals a superior long-range property than SRSSP mode even with large asymmetry. But the advantage vanishes gradually with enlarged asymmetry Δh.

4. Conclusion

In conclusion, the asymmetric double metal gratings are proposed to support LRSSP. Symmetric structure is simple [14]–[30], however, the asymmetry can provide a new degree of freedom to control SSP mode on this kind of double-corrugated plasmonic structure. Besides, the propagation losses of SRSSP can be reduced largely within asymmetric regime. For LRSPP in optical band, symmetric mode on the double layer interfaces is suffer from the strictly symmetric bounding dielectric and is highly dependent on the thickness of metal film as indicated as t in Fig. 1(b). However, LRSSP mode on the doubly-corrugated plasmonic structure shows good tolerance of asymmetry according to our studies in THz spectrum. The long-range propagation advantage of LRSSP mode vanishes with the increased degree of asymmetry. SRSSP mode occupies its location and also shows distinct characteristics in the dispersion band. The presented studies can pave the way for the further excitation of SSP mode by using injected energy beam based on the proper beam-wave dispersion matching on the asymmetric structure. Besides, how to deal with the losses of SSP mode with every plasmonic waveguide will determine its final performances for practical applications. Its demonstrated competitive low-loss propagation on the asymmetric double corrugated structure can open up new avenues to develop some novel LRSSP-based plasmonic devices such as ultra-sensitive sensors and intense compact sources based on extremely slow light-matter interaction in THz spectrum.

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