Odd-mode and even-mode spoof surface plasmon polaritons supported by complementary plasmonic metamaterial with underlayer ground

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Abstract  In this letter, odd-mode and even-mode spoof surface plasmon polaritons (SSPPs) supported by complementary plasmonic metamaterial with underlayer ground are investigated. The dispersion characteristics and electric field distributions of the odd-mode and even-mode SSPPs are studied. Different high-efficiency conversion structures are proposed to realize the excitation of odd-mode and even-mode SSPPs transmissions. The odd-mode and even-mode SSPPs transmission lines are simulated and measured. The measured insertion losses of odd-mode transmission line are within 2.58 ± 1.23 dB from 3.0 to 10.0 GHz. The measured insertion losses of even-mode transmission line are within 1.66 ± 1.18 dB from 2.0 to 12.0 GHz. The simulation and measurement results validate the high-efficiency excitation and excellent propagation performance of odd-mode and even-mode SSPPs on the complementary plasmonic metamaterial with underlayer ground in the microwave frequencies.

Keywords: odd-mode, even-mode, SSPPs, conversion, transmission

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Surface plasmon polaritons (SPPs) are intensively localized surface waves which propagate along the interface of air-metal and decay exponentially in the transverse direction. It has a wide range research in the optical field, and has broad application prospects in the fields of biomedical sensing, chemical sensing and nano photonics [1, 2, 3, 4, 5, 6, 7, 8]. Hereafter, the interested frequencies of SPPs is reduced to terahertz and microwave frequencies. A new concept for the surface plasmon polariton-like bound surface states was proposed, which is called spoof surface plasmon polaritons (SSPPs) [9, 10]. The significant advantages of SSPPs structure are that its dispersion characteristics and electric field distributions of odd-mode and even-mode SSPPs supported by complementary plasmonic metamaterial with underlayer ground are not studied. The transmission of the odd-mode and even-mode based on this structure are also not implemented.

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The odd-mode and even-mode SSPPs transmission can also be supported by the SSPPs transmission lines, which are similar to the classical transmission lines. The dispersion characteristics and electric field distributions of odd-mode and even-mode SSPPs supported by complementary plasmonic metamaterial are investigated. And then, the transmission of the odd-mode SSPPs is achieved by slot lines on metal plates [31, 32]. However, the dispersion characteristics and electric field distributions of odd-mode and even-mode SSPPs supported by complementary plasmonic metamaterial with underlayer ground are not studied. The transmission of the odd-mode and even-mode based on this structure are also not implemented.

In this letter, odd-mode and even-mode SSPPs supported by complementary plasmonic metamaterial with underlayer ground are investigated. According to its structural characteristics, we call it as microstrip-type metal-double-grating. The dispersion characteristics and electric field distributions of the odd-mode and even-mode SSPPs are analyzed. Different high-efficiency conversion structures are proposed to realize the excitation of odd-mode and even-mode SSPPs transmissions. The odd-mode and even-mode SSPPs transmission lines are simulated and fabricated. The measurement topology and measured scattering parameters (S-parameters) are given.
2. Parametric study

2.1 Microstrip-type metal-double-grating structure

A unit cell of microstrip-type metal-double-grating, composed of complementary symmetric grooves of depth \( h \) and width \( a \), is depicted in Fig. 1. Each side of the double-grating can be regarded as a single-grating. The thickness of the metal-single-grating and underlayer ground is \( t \), and the width of edge metal strip is \( w \). The distance between two single-gratings is \( s \). The period of the unit cell is \( p \). Different dispersion characteristics can be obtained by varying the depth \( h \), width \( a \) of the grooves and the distance \( s \) between two single gratings. The microstrip-type metal-double-grating has many degrees of freedom to tailor the dispersion characteristics, further extending its scope of application.

2.2 Dispersion characteristics of the microstrip-type metal-double-grating

Dispersion characteristics of the microstrip-type double-grating can be analyzed by eigenmode method of full wave simulation, as shown in Fig. 2. The external area is bounded by periodic boundary in the transmission direction of electromagnetic wave (\( x \)-direction), and perfect magnetic conductor boundary (PMC) in the \( y \)-direction, with perfect electric conductor (PEC) in the \( z \)-direction.

The relationships between the structure size of microstrip-type double-grating and the dispersion characteristics of odd-mode and even-mode SSPPs are given in Fig. 3, respectively. From Fig. 3, it can be found that the dispersion curves deviate significantly from the light and eventually approach the cutoff frequency, which indicating that the double-grating supports the propagation of odd-mode and even-mode SSPPs.

The thickness of the metal-single-grating and underlayer ground \( t \) is 0.018 mm and width of edge metal strip \( w \) is 0.36 mm. The period \( p \) is 3.0 mm. The thickness of the F4B substrate (dielectric constant 2.65 and loss tangent 0.003) \( d \) is 0.5 mm. We can find that the cutoff frequencies of even-mode SSPPs are slightly higher than the odd-mode. When \( a \) is 1.2 mm and \( s \) is 0.1 mm, varying the depth \( h \), the odd-mode and even-mode SSPPs dispersion relationships are shown in Fig. 3(a) and (b). The cutoff frequencies of odd-mode and even-mode dispersion relationships are shown in Fig. 3(c) and (d).
SSPPs are significantly declined while the \( h \) is increased. When \( h \) is 3.0 mm and \( s \) is 0.1 mm, varying the width \( a \), the odd-mode and even-mode SSPPs dispersion relationships are given in Fig. 3(c) and (d). When \( a \) is increased, the cutoff frequencies of odd-mode and even-mode SSPPs are declined. When \( h \) is 3.0 mm and \( a \) is 1.2 mm, varying the distance \( s \), the odd-mode and even-mode dispersion relationships are shown in Fig. 3(e) and (f). When \( s \) is increased, the cutoff frequency of odd-mode SSPPs is increased but the cutoff frequency of even-mode SSPPs is declined. Combining Fig. 3(a), (b), (c), (d), (e) and (f), we can find that the depth \( h \), the width \( a \) of the grooves and the distance \( s \) between two single-gratings are obvious for the regulation of the odd-mode and even-mode SSPPs dispersion characteristics.

3. Electric field distributions of odd-mode and even-mode SSPPs

When the frequency of the propagation wave is lower than the cutoff frequency, it can be supported by the microstrip-type metal-double-grating. In order to investigate the electric field distributions of the odd-mode and even-mode SSPPs supported by the double-grating. The field distributions of different modes are given by simulation in Fig. 4. From Fig. 4, we can find that the electric field distributions of the odd-mode and even mode SSPPs are completely different. For the odd-mode, the phases of electric field on both sides of the double-grating are opposite. The electric field energy is mainly concentrated on the edge of the comb-like metal. On the other hand, for the even mode, the electric fields on both sides of the double-grating are in the same phases. The electric field energy is mainly concentrated on the edge of the groove.

4. Transmission and conversion structure

In order to achieve odd-mode and even-mode SSPPs transmissions supported by microstrip-type metal-double-grating, different high-efficiency conversion structures are proposed to convert the guided waves to the double-grating. The microstrip-type metal-double-grating and conversion structures are printed on 0.5 mm thick F4B substrate with dielectric constant of 2.65 and loss tangent of 0.003. The thicknesses of ultrathin copper strips and underlayer ground are selected to be 0.018 mm.

4.1 Odd-mode transmission and conversion structure

The odd-mode SSPPs transmission line is an axisymmetric structure and consists of three parts: microstrip line with 50 \( \Omega \) characteristic impedance, regard as the excitation waveguide, is denoted as Part 1, as shown in Fig. 5(a). Part 2 is the conversion structure, which is composed of balun structure and gradual structure, as shown in Fig. 5(a). The balun structure is used to feed electromagnetic waves to the double-grating with the same amplitudes and opposite phases. The gradual structure is used to obtain the impedance matching between the balun structure and double-grating, in which the depth of grooves is from \( h_1 \) to \( h_2 \) with a step of 0.36 mm, as shown in Fig. 5(b) and (c). Part 3 is the microstrip-type metal-double-grating transmission line, in which \( h \) is 2.8 mm. \( a \) is 1.2 mm, \( p \) is 3.0 mm, \( s \) is 0.1 mm, \( w \) is 0.36 mm, as shown in Fig. 5(a) and (b). The S-parameters of the back to back balun structure and the odd-mode SSPPs transmission line are simulated by using the full wave simulation, as shown in Fig. 6. The low frequencies of the transmission line is limited by the bandwidth of the balun structure. The cutoff frequency is in accordance with the analysis of odd-mode dispersion characteristics. The simulated \( E_z \) field distributions and S-parameters of transmission line indicate that the proposed conversion structure can realize the excitation of odd-mode SSPPs transmission.

4.2 Even-mode transmission and conversion structure

The even-mode SSPPs transmission line is also an axisymmetric structure and consists of three parts: Part1 is the microstrip line with 50 \( \Omega \) characteristic impedance, which is regard as the excitation waveguide, as shown in Fig. 8(a). Part 2 is the conversion structure, which is composed of power divider and gradual structure, as shown in Fig. 8(a) and (b). The power divider is used to feed
electromagnetic waves to the double-grating with the same amplitudes and phases. The gradual structure is used to obtain the impedance matching between the power divider and double-grating, in which the depth of grooves is from $h_3$ to $h_4$ with a step of 0.25 mm. Part 3 is the microstrip-type metal-double-grating transmission line, in which $h$ is 2.8 mm, $a$ is 1.2 mm, $p$ is 3.0 mm, $s$ is 0.1 mm, and $w$ is 0.36 mm. The S-parameters of the back to back power divider and the even-mode SSPs transmission line are simulated by using the full wave simulation, as shown in Fig. 9. The cutoff frequency is in accordance with the analysis of even-mode dispersion characteristics. The S-parameters indicate that electromagnetic waves can propagate efficiently along the transmission line. The simulated $E_z$ field distributions of the even-mode transmission line are shown as Fig. 10. The simulated field distributions and S-parameters of transmission line indicate that the proposed conversion structure can realize the excitation of even-mode SSPs transmission.

Fig. 5. The odd-mode SSPs transmission line and conversion structure. (a) Top and bottom view of transmission line, in which $L_1 = 8.65$ mm, $L_2 = 44.54$ mm, $L_1 = 67.8$ mm. (b) Conversion structure, in which $w_3 = 1.5$ mm, $r_3 = 2.35$ mm, $r_2 = 2.72$ mm, $r_1 = 4.19$ mm, $r_4 = 1.63$ mm, $h_1 = 0.45$ mm, $h_2 = 2.61$ mm, $h$ is 2.8 mm, $a$ is 1.2 mm, $p$ is 3.0 mm, $s$ is 0.1 mm, and $w$ is 0.36 mm. (c) Bottom view of the balun structure, in which $r_5 = 2.35$ mm, $r_6 = 1.37$ mm and $s_1 = 0.1$ mm.

Fig. 6. Simulated S-parameters by using the full wave simulations. (a) Back to back balun structure. (b) Odd-mode SSPs transmission line.

Fig. 7. The $E_z$ electric field distributions of the odd-mode SSPs transmission line on the surface of dielectric substrate at 9.0 GHz.

Fig. 8. The even-mode transmission line and conversion structure. (a) Top and bottom view of transmission line, in which $L_4 = 6$ mm, $L_5 = 30.1$ mm, $L_6 = 67.8$ mm. (b) Conversion structure, in which $w_1 = 1.5$ mm, $h_3 = 0.55$ mm, $h_4 = 2.55$ mm, $h$ is 2.8 mm, $a$ is 1.2 mm, $p$ is 3.0 mm, $s$ is 0.1 mm and $w$ is 0.36 mm.

Fig. 9. Simulated S-parameters by using the full wave simulations. (a) Back to back power divider. (b) Even-mode SSPs transmission line.
5. Fabrication and measurement

The odd-mode and even-mode microstrip-type metal-double-grating transmission lines are fabricated according to the parameters of Fig. 5 and Fig. 8, as shown in Fig. 11. They are measured by an Agilent Technologies E8363B network analyzer, as shown in Fig. 12. The simulated and measured S-parameters of odd-mode and even-mode SSPPs transmission lines are given in Fig. 13 and Fig. 14, respectively. The measured S-parameters are close to the simulation, indicating that the transmission lines have relatively good transmission performance for odd-mode and even-mode SSPPs. The measured insertion losses of odd-mode transmission line are within 2.58 ± 1.23 dB from 3.0 to 10.0 GHz. The measured insertion losses of even-mode transmission line are within 1.66 ± 1.18 dB from 2.0 to 12.0 GHz. Differences between the simulated and measured insertion losses are mainly caused by the SMA connectors and fabrication tolerances.

6. Conclusion

In this letter, the odd-mode and even-mode SSPPs supported by microstrip-type metal-double-grating are investigated. The dispersion characteristics and electric field distributions of the odd-mode and even-mode SSPPs are analyzed and simulated. Different dispersion characteristics can be obtained by adjusting the parameters of the double-grating. In order to achieve odd-mode and even-mode SSPPs transmission, different high-efficiency conversion structures are proposed to convert the guided waves to the metal-double-grating. The odd-mode and even-mode SSPPs transmission lines are simulated and measured. The simulation and measurement results are in good agreement, which validate the high-efficiency excitation and excellent propagation performance of odd-mode and even-mode SSPPs on the microstrip-type metal-double-grating in the microwave frequencies. The odd-mode and even-mode SSPPs transmissions lay the foundation to develop odd-mode and even-mode SSPPs devices and circuits in the microwave and terahertz regimes in the future.
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