A Polarization Independent Surface Wave Coupler Based on a Phase Gradient Metasurface

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A phase gradient metasurface (PGM) is an anisotropic metallic array structure with sub-wavelength thickness, which can produce an in-plane phase gradient in the incident wave. It can be used to control the shape of the wave front, the propagation direction, and the polarization of the reflected/refracted waves with more freedom. In this paper, the combined-split-resonant-rings (CSRR) is proposed as the sub-unit resonators so as to achieve the PGM. At the central frequency $f = 3.3$ GHz, the PGM is designed to work as a surface electromagnetic wave (SEMW) coupler. The necessary momentum for surface wave coupling is compensated by the phase gradient provided by the PGM. The coupling efficiency extracted from the simulated reflection coefficient and the distributions of the electromagnetic fields indicate that this PGM is a highly-efficient and polarization independent SEMW coupler under normal incidence. Because of the characteristics of high coupling efficiency, polarization-independence, and ultra-thin structure, significant applications in invisibility can be envisaged.

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I. INTRODUCTION

A surface electromagnetic wave (SEMW) [1] is a type of electromagnetic wave (EMW) propagating along the interface of two different media and attenuating away from the interface, of which the energy is totally localized near the interface. A necessary existence condition for a SEMW is that the media forming the interface have different signs of their permittivities or permeabilities. The vast majority of research in the last century was focused on p-polarized SEMWs, i.e., surface plasmon polaritons (SPPs) [2–4] involving metallic media. However, the SEMW involving magnetic media has attracted more attention until the recent advent of metamaterials [5], mainly because of their important roles in many applications, such as super-lenses or cloaking devices [6]. Attenuated total reflection (ATR) and grating diffraction [7, 8] are the most popular approaches used to couple the volume electromagnetic waves into SEMWs. However, these approaches cannot be easily implemented in the microwave frequency region due to bulky configurations. This hinders the application of SEMWs. In this regard, an ultra-thin, polarization independent SEMW coupler based on a phase gradient metasurface (PGM) [9] is achieved in this work.

The PGM is an anisotropic metallic array structure with sub-wavelength thickness, which adds an abrupt phase shift [10–21] to the incident wave along the wave propagation path. It is designed on the basis of the generalized version of the reflection law and refraction law [10]. Conventional optical components such as lenses, prisms, and mirrors, as well as diffractive elements such as gratings, etc., rely on gradual phase changes accumulated along the optical path to shape the wavefront [13]. Thus a propagation distance larger than a wavelength is necessary. A metamaterial can also realize singular bending of a light path, which has a lot of applications in negative refraction, super resolve imaging, and invisible cloaking. However, the ability to control the propagation of light is still limited by classical reflection and refraction laws and the development of the metamaterials. Recently, the PGM was proposed by Yu et al. [10], which provides us with a method of controlling the propagation of EMWs with more potential. It introduces an abrupt phase shift along the light path, of which the thickness is much less than a wavelength. For a PGM, a longer propagation distance is no longer required, and the propagation of the wave can be controlled with more freedom. As a beam of the wave is incident onto the PGM, via accurate design of the phase gradient, the reflected waves and the refracted waves can propagate along an arbitrary direction under certain incident angles.

Since the PGM was put forward for the first time, it has attracted extensive attention in the academic field. Yu et al. achieved a PGM using V-shape optical antennas, which can make both the refracted wave and the reflected wave propagate along an arbitrary direction via design [10–12]. A vortex beam [13, 14] was created by two-dimensional phase gradient design. Then, in their subsequent works, PGM based aberration-free planar lenses and axicons were demonstrated in Ref. [15], and a birefringment array of two dimensional (V- and Y-shaped) optical antennas served as broadband, anisotropic optical elements used to locally tailor the amplitude, phase, and polarization of light was theoretically and experimentally studied in Ref. [16]. The PGM designed using H-shaped metallic unit cells laid on a dielectric substrate backed with a metal groundsheet can make the reflected waves propagate along an arbitrary direction under normal incidence [9]. Wang et al. designed a reflective PGM using a split resonant ring (SRR), which served as a high efficiency SEMW coupler with a specific polarization condition.

In this paper, a polarization independent SEMW coupler based on a PGM is achieved using combined-split-resonant-rings (CSRR) as the sub-unit resonators. Under normal incidence, the necessary in-plane wave-vector for the SEMW coupling is compensated by an additional in-plane phase gradient provided by the PGM. The coupling efficiency was extracted from the simulated reflection coefficient. The simulated results indicate that this SEMW coupler can effectively enhance the coupling efficiency with an ultra-thin thick structure. Most importantly, it is polarization independent.

II. THE DESIGN PRINCIPLE

According to the classical reflection and refraction laws, the phase shift is continuous along the propagation path of EMWs, i.e., the phase gradient is zero. However, by the
generalized version of the reflection law, the phase gradient $d\Phi/dx$ is added to the incident wave in the $x$-direction by the PGM, as described in Fig. 1. The reflected wave can be anomalously reflected in any direction via accurate phase gradient design. If the in-plane wave-vector after compensation is larger than the wavevector in free space, the incident waves will be coupled into the SEMW along the PGM. Suppose that a beam of the EMW illuminates onto a two-dimensional PGM with an incidence angle $\theta$ and an incidence polarization azimuth angle $\phi$, the in-plane wave vector of the reflected wave can be expressed as

$$k_{\parallel} = k_x \hat{x} + k_y \hat{y},$$

where the magnitudes of the in-plane wave-vector in $x$- and $y$-directions are

$$k_x = k_0 \sin \theta \cos \phi + \frac{d\Phi_x}{dx},$$
$$k_y = k_0 \sin \theta \sin \phi + \frac{d\Phi_y}{dy},$$

(1a)
(1b)

where $\theta$ is the incidence angle, $\phi$ is the incidence polarization azimuth angle, i.e., the direction of the incident plane. When the amplitude of the in-plane wavevector $k_{\parallel} > k_0$, the incident wave is coupled into the SEMW propagating along the $k_{\parallel}$ direction on the PGM. In contrast, anomalous reflection happens when $k_{\parallel} < k_0$.  

FIG. 1: Schematic diagram used to describe the principle of the PGM based SEMWs coupler.

As the conclusion above is simplified into the instance for the one-dimensional PGM under normal incidence, The in-plane wave-vector is expressed as

$$k_x = \frac{d\Phi_x}{dx}.$$  

(2)

Suppose $k_x = ck_0$, $c$ is an arbitrary positive constant. When $c > 1$, the derived reflection angle is larger than 90°, the incident wave is coupled into the surface wave. However anomalous reflection appears if $c < 1$, the reflected angle can be easily obtained, that is $\theta_r = \arcsin c$. 


III. DESIGN OF THE PGM BASED SEMW COUPLER

III-1. Design of the sub-unit resonator

In order to achieve a polarization independent PGM based SEMW coupler, the CSRR metallic pattern with 90 degree rotation symmetry is designed by a combination of four split resonant rings with the same size dimension. A resonator consisting of a CSRR metallic pattern, a metal groundsheet, and a dielectric spacer is designed as the sub-unit resonator of the PGM. In the resonance frequency range of the resonators, the phase of the reflected wave can be manipulated. As shown in Fig. 2, (a) gives a front view of the sub-unit resonator, and (b) gives a side view. The sub-unit resonator is composed of three layers: the CSRR copper metallic pattern, copper groundsheet, and a FR4 substrate ($\varepsilon_r = 4.3$, $\tan \delta = 0.025$). The thickness of the groundsheet is $m$. $d$ is the thickness of the dielectric substrate. $a$ is the repetition period of the sub-unit resonator. The thickness of the CSRR copper pattern is $t$. The metal wire width of the CSRR is $w$. Other geometric dimensions of the CSRR are depicted in the figures.

![FIG. 2: Schematic of the sub-unit resonator: (a) the front view, (b) the side view.](image)

III-2. Design of the PGM

For the sub-unit cell designed above, the values of the constant geometric dimensions by optimization are given as follows: $d = 2.8 \text{ mm}$, $t = 0.12 \text{ mm}$, $b = 4.7 \text{ mm}$, $w = 0.3 \text{ mm}$, $a = 10 \text{ mm}$, and $m = 0.5 \text{ mm}$. The reflected phase changes with the arm-length $l$ and the slit-width $s$ of the CSRR. In order to obtain the phases of the reflection coefficient with different parameter values of $l$ and $s$, we perform full-wave numerical simulations using CST Microwave Studio in 2.5–3.5GHz. The boundary conditions are unit cell in the $x$- and $y$-directions. The EMWs are normally incident onto the sub-unit resonators designed above. According to the simulated results, the phase difference between adjacent unit cells is designed to be $\pi/4$ at the frequency $f = 3.3 \text{ GHz}$. Eight different sub-unit cells are selected in order to realize a total $2\pi$ phase shift. Their simulated reflection phases versus
frequency from 3.25GHz to 3.35GHz are given in Fig. 3. From the simulated results, the
reflection phases at the designed frequency $f = 3.3$ GHz are $\Pi_1 = -645^\circ$, $\Pi_2 = -690^\circ$, $\Pi_3 = -735^\circ$, $\Pi_4 = -780^\circ$, $\Pi_5 = -825^\circ$, $\Pi_6 = -870^\circ$, $\Pi_7 = -915^\circ$, $\Pi_8 = -960^\circ$. The corresponding phase shifts between adjacent sub-unit cells are $\Delta\Pi_{12} = \Delta\Pi_{23} = \Delta\Pi_{34} = \Delta\Pi_{45} = \Delta\Pi_{56} = \Delta\Pi_{67} = \Delta\Pi_{78} = \Delta\Pi_{81} = \pi/4$. Consequently, eight group parameter values for $l$ and $s$ are given in Table I.

![Simulated reflection phases versus frequency for EMW normal incidence onto the periodically arranged CSRR sub-unit cells with various $l$ and $s$.](image)

**FIG. 3:** Simulated reflection phases versus frequency for EMW normal incidence onto the periodically arranged CSRR sub-unit cells with various $l$ and $s$.

<table>
<thead>
<tr>
<th>$l$</th>
<th>0.544</th>
<th>0.775</th>
<th>0.945</th>
<th>1.116</th>
<th>1.276</th>
<th>1.510</th>
<th>1.885</th>
<th>2.547</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>3.379</td>
<td>1.665</td>
<td>1.120</td>
<td>0.803</td>
<td>0.614</td>
<td>0.439</td>
<td>0.281</td>
<td>0.154</td>
</tr>
</tbody>
</table>

**TABLE I:** Values for the eight group parameters of $l$ and $s$.

The selected eight sub-unit cells placed in the $x$-direction in the order of reflection phase form the super-unit of the PGM, as shown Fig. 4. The phase difference between adjacent sub-unit cells is approximately equal to $\pi/4$, and the repetition period of the sub-unit cells is $a$. Thus the phase gradient designed is $\pi/4a = 25\pi$ by calculation. The volume wave-vector in free space at $f = 3.3$ GHz is $2\pi f/c = 22\pi$, which is less than the in-plane wave-vector provided by the designed phase gradient. Consequently, the normal incident wave is coupled into the SEMW propagating along the PGM. Therefore, the PGM works as a SEMW coupler under EMW normal incidence.
IV. SIMULATION AND RESULTS ANALYSIS

For the designed super-unit of the PGM based SEMW coupler, we perform full-wave numerical simulations using CST Microwave Studio in 2.5–4.1 GHz. The boundary conditions in the $x$- and $y$-directions are all unit cells. The simulated reflection coefficients $S_{11}$ for TE and TM waves of normal incidence are given in Fig. 5. The SEMW coupling efficiency can be extracted from the simulated reflection coefficient $S_{11}$. The dip of the $S_{11}$ corresponds to the peak of the coupling efficiency. Consistent with our design, the simulated peak of the coupling coefficient is located near the designed central frequency $f = 3.3$ GHz except for a tiny frequency offset. This is mainly because of the coupling between the adjacent sub-unit cells of the super-unit is weaker than that between the sub-unit cells within the same size while calculating the reflected phases.

At the peak of the coupling coefficient, we can easily conclude that the incident wave is almost completely coupled into the SEMW propagating along the PGM. This is also effectively verified by the distribution of the electromagnetic fields given in Fig. 6 and
Fig. 7. It is observed from Fig. 5 that the coupling peaks for all the TE and TM incident waves are located at the same frequency. By this reckoning, this PGM based SEMW coupler is polarization independent. This is the most outstanding characteristic in our design. It is mainly attributed to the symmetric structure with 90° rotation of the CSRR sub-unit cells. Under TE wave normal incidence, the coupling efficiency of over 0.8 is predicted to be 15%, which is 12% for TM wave normal incidence. The 5dB relative bandwidth of the coupling efficiency is about 0.1 and 0.08 for the TE and TM incident waves, respectively. Due to the perturbations of the phase gradients around the central frequency, there are several perturbations of the reflectivity around the central frequency. Consequently, several coupling peaks appear around the central coupling peak as a result. In addition, because of the specific 90° rotary symmetric structure, the polarization of the reflected wave is partially rotated. The cross-polarization reflection is much less than the co-polarization reflection, so it cannot affect the SEMW coupling efficiency effectively.

Fig. 6 and Fig. 7 show the distributions of the electric field and magnetic field at frequency $f = 3.3$ GHz under TE and TM normal incidence, respectively. We can find from Fig. 6 that under TE wave normal incidence, the incident electric field is polarized in the $y$-direction and the incident magnetic field is polarized in the $x$-direction. On the surface
of the PGM, the magnetic field rotates to the \( z \)-direction. Thus the waves propagate along the \( x \)-direction. Accordingly, the incident TE wave is coupled into the SEMW propagating along the PGM. Likewise, the distributions of the electric field and magnetic field under TM wave normal incidence are shown in Fig. 7. From the figure, one can see that the electric field and magnetic field are, respectively, polarized in the \( x \) - and \( y \)-directions. On the surface of the PGM, the electric field turns towards the \( z \)-direction with 90° rotation. Therefore, the waves on the surface of the PGM propagate along the \( x \)-direction. Accordingly, the incident TM wave is also coupled into the SEMW propagating along the PGM. From the field \( z \)-component on the PGM, the field is significantly enhanced compared to the incident field, and the energy is totally confined near the surface because of the SEMW coupling.

V. CONCLUSION

In summary, a polarization independent PGM is proposed to serve as a polarization independent SEMW coupler. The CSRR structure is designed as the sub-resonators to design the PGM. The phase gradient is designed by calculating the reflected phases of the sub-resonators with different \( l \) and \( s \) values under normal incidence. The coupling efficiency extracted from the simulated reflection coefficient indicates that the PGM based SEMW coupler is polarization independent, and the bandwidth of the coupling efficiency over 0.8 is 15% and 12%, respectively, for TE and TM waves of normal incidence. The coupling efficiency is up to 99% at the coupling peaks. The given distributions of the electromagnetic fields are analyzed, which further verifies our design. To sum up, because of the characteristics of ultra-thin thickness and polarization independence, this PGM based SEMW coupler can be envisaged to have wide applications in invisibility.

Acknowledgments

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