

# Beam-Steering Multi-Layer Metasurface at 35GHz

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**Abstract** - The coaxial annular aperture structure is applied in this paper to construct multi-layer phase-gradient metasurfaces with high transmission efficiency realizing anonymous beam steering at 35GHz. Simulation results confirm that normally incident plane wave is successfully refracted by 19° and 60°, which are in good agreement with the theoretical design by the generalized Snell's law.

**Index Terms** — Generalized Snell's law, beam steering, metasurface.

## 1. Introduction

Controlling and molding the wave front of a transmitted electromagnetic beam are of continuing interests throughout the entire spectrum. Conventional wave front modulator is achieved via propagation through media of given refractive coefficient, such as lenses and prisms, which are unfortunately bulky. Metasurfaces, artificial two-dimensional composites consisting of unit cells of sub-wavelength, may possess arbitrary values of permittivity and permeability and hence offer much freedom for beam steering [1]. A two-dimensional array composed of V-shaped antennas has demonstrated the validity of the so-called generalized Snell's law of refraction, by imparting a designed phase-gradient discontinuity [2, 3]. However, operating with cross-polarized fields has a severe efficiency limitation which hinders the practical application of the proposed structure [4]. In order to overcome this limitation, a stack of metasurface layers with abrupt varying material properties utilizes the coupling among ultra-thin layers to realize beam steering with high efficiency [5, 6, 7]. Multi-layer transmission metasurfaces at optical frequency range were proposed in [5, 7], while an L-band multi-layer structure was reported in [6]. In this paper, we present design and characterization of multi-layer phase-gradient metasurfaces with high efficiency at 35GHz, and demonstrate numerically that it can redirect a normally impinging plane wave to an arbitrary angle of refraction.

## 2. Design of the Multi-layer Metasurface

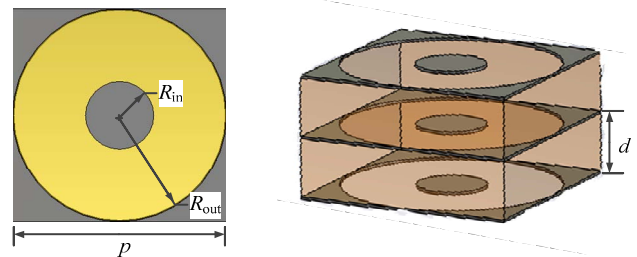
According to the generalized Snell's law, wave front can be modified by carefully design of the phase gradient of the transmission coefficient along one direction, which reads,

$$n_i \sin \theta_i - n_t \sin \theta_t = \frac{1}{k_0} \frac{d\Phi}{dx} \quad (1)$$

where  $\theta_i$  and  $\theta_t$  are the incident and the transmission angles,

$n_i$  and  $n_t$  are the refractive coefficients of two media separated by the metasurface, and  $d\Phi/dx$  is the phase gradient along the metasurface ( $x$ -direction).

Since the coaxial annular apertures (CAAs) have high transmission efficiency and their phases of the transmission coefficient vary smoothly with the change of inner radius, we adopt this structure to build the unit cell of metasurface. Fig. 1 shows the schematic of the unit cell structure.  $R_{in}$  and  $R_{out}$  are the inner and outer radius, respectively,  $p$  is the unit cell period, and  $d$  is the substrate thickness ( $\epsilon_r=2.2$ ).



(a) Top view of the unit cell (b) Side view of the unit cell  
Fig. 1. The schematic of the unit cell structure.

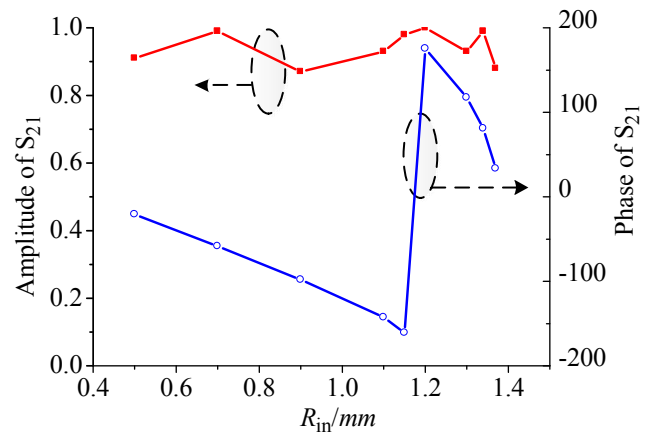


Fig. 2. Simulated amplitude and phase of the transmission coefficient  $S_{21}$  for varying  $R_{in}$  when  $p=3\text{mm}$ ,  $R_{out}=1.5\text{mm}$ , and  $d=0.8\text{mm}$ .

For the convenience of future fabrication, the following geometrical parameters are selected where  $p=3\text{mm}$ ,  $R_{out}=1.5\text{mm}$ , and  $d=0.8\text{mm}$ . Fig. 2 shows the simulated amplitude and phase of the transmission coefficient  $S_{21}$  for varying  $R_{in}$  when  $p=3\text{mm}$ ,  $R_{out}=1.5\text{mm}$ , and  $d=0.8\text{mm}$  at 35GHz. With the gradually changing of inner radius, the transmission phase changes over the whole  $2\pi$  range, while the transmission amplitude is maintained above 0.85.

TABLE I  
Inner radius of the unit cell forming the super cells  
for beam bending at  $\theta_t=19^\circ$  and  $\theta_t=60^\circ$

$\theta_t$	$R_{in}$ (mm)							
	#1	#2	#3	#4	#5	#6	#7	#8
$19^\circ$	1.10	0.95	0.70	0.50	1.37	1.34	1.28	1.22
$60^\circ$	0.80	1.36	1.22					

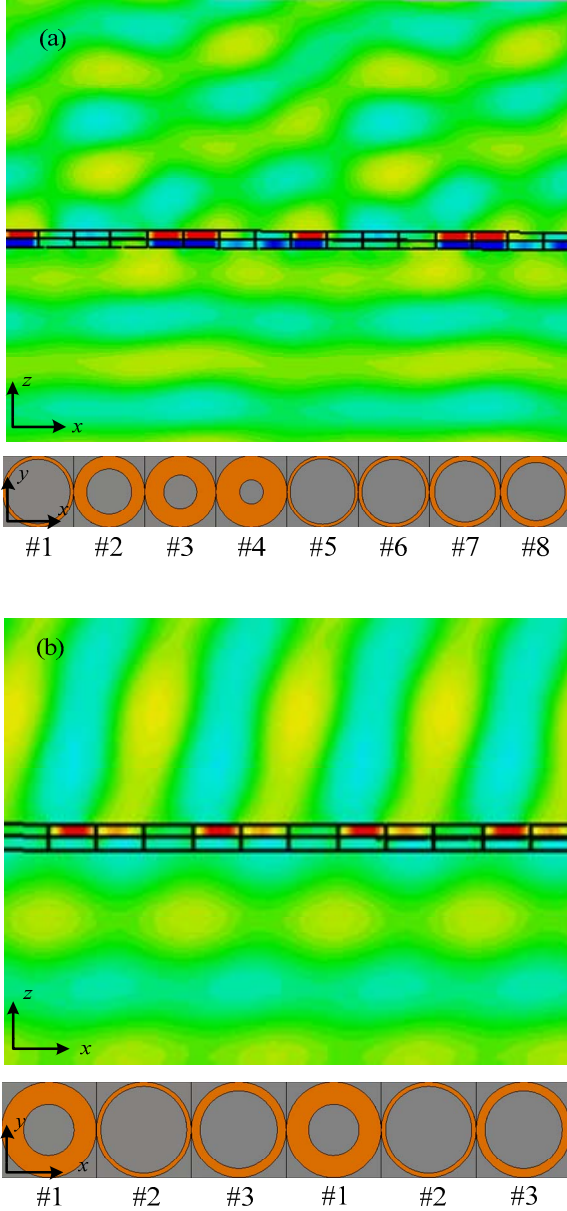


Fig. 3. Simulated magnetic field distribution ( $H_y$ ) for beam bending at (a)  $\theta_t=19^\circ$  and (b)  $\theta_t=60^\circ$ .

According to the generalized Snell's law and the selected geometrical parameters of the unit cell, eight element antennas and three element antennas are chosen to form the super cell. The resulting multi-layer metasurfaces are expected to redirect a normally incident plane wave at  $\theta_t=19^\circ$  and  $\theta_t=60^\circ$ , respectively. The values of inner radius, which vary along the  $x$ -direction, are shown in Table I.

### 3. Numerical Validation

Through periodically repeating the super cell along  $x$ - and  $y$ -directions, the multi-layer metasurfaces are successfully constructed. Fig. 3 shows the simulated magnetic fields distributions ( $H_y$ ) for a normally incident plane wave with  $y$ -directed magnetic field. The transmission angles of  $19^\circ$  and  $60^\circ$  are in excellent agreement with theoretical prediction. The simulated transmission efficiencies are above 70% at 35GHz.

### 4. Conclusion

In this paper, we present a three-layer phase-gradient metasurfaces with high transmission efficiency based on the CAAs structures working at 35GHz. The size of each unit cell is  $3\text{mm}\times 3\text{mm}$ , and the outer radius is 1.5mm, which are in deep sub-wavelength range. The transmission phase of the unit cell covers the whole  $2\pi$  range, while maintaining the transmission amplitude above 0.85. According to the generalized Snell's law, we designed two phase-gradient metasurfaces which are capable of redirecting a normally incident plane wave by  $19^\circ$  and  $60^\circ$ , respectively, which are finally confirmed by the full wave simulation. The proposed multi-layer metasurface may pave the way for compact wave front modulators, such as beam deflection, focusing and super scattering.

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