Generation of spatial Bessel beams using holographic metasurface

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Abstract: We propose to use backward radiations of leaky waves supported by a holographic metasurface to produce spatial Bessel beams in the microwave frequency regime. The holographic metasurface consists of a grounded dielectric slab and a series of metal patches. By changing the size of metal patches, the surface-impedance distribution of the holographic metasurface can be modulated, and hence the radiation properties of the leaky waves can be designed to realize Bessel beams. Both numerical simulations and experiments verify the features of spatial Bessel beams, which may be useful in imaging applications or wireless power transmissions with the dynamic focal-depth controls.

OCIS codes: (090.2910) Holography, microwave; (160.3918) Metamaterials; (240.6690) Surface waves; (050.6624) Subwavelength structure.

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1. Introduction

Bessel beam is a typical non-diffracting beam, which was firstly proposed as a special solution of the Helmholtz equation [1]. Considering that the Bessel beam could be taken as the Fourier transform of a ring, it could be generated by using an annular slit placing in the focal plane of a lens due to the Fourier transforming property [2]. Viewed as a superposition of plane waves whose wave vectors lie on a cone, Bessel beams could also be generated using axicon [3, 4] or binary holograms [5] illuminated by Gaussian beam. In radio frequencies, based on the similar mechanism, some approaches like the axicon [4, 6], binary hologram [7, 8], localized modes [9], guided modes [10], metallic subwavelength apertures [11–13] and metasurfaces [14–16] have been used to generate the Bessel beams.

Theoretically, any conical beams having a diamond-shaped overlapping region can form a pseudo Bessel beam. For leaky waves [17], these conical beams would be in backward directions. The conical beams have been thoroughly studied in many earlier works on leaky waves [18–21]. However, the Bessel beams interfered by backward leaky waves, either uniform or periodic, were seldom discussed. Recently, the generation of Bessel beams using leaky radial waveguide has been investigated [15, 16], which could be considered as an uniform leaky-wave antenna. The reflection on the edge forms standing waves, meeting the requirement of a Bessel function distribution. The work on periodic subwavelength metallic aperture [11] is actually a period leaky-wave structure. Meanwhile, the leaky-wave radiations based on sinusoidally modulated impedance surface have been investigated [22–24], which has even been used in designing a tunable graphene leaky-wave antenna [25]. However, to our best knowledge, the Bessel beam based on holographic metasurface has not been investigated.

![Fig. 1. The conical beam generated from leaky waves by the holographic metasurface. The TM surface wave is excited by a monopole located in the metasurface center. The metasurface is modulated by the sinusoidally surface impedance to radiate backward leaky waves, which are interfered with each other to form a Bessel beam.](image)

In this work, we propose a conical beam shaping by using holographic metasurface to generate spatial Bessel beam, in which a monopole located in the metasurface center is used to excite the surface wave. As reference wave, the surface wave is then modulated by the holographic metasurface, and the conical backward leaky wave is radiated as the object wave. Due to the circular symmetry, these conical leaky waves are interfered with each other to form a Bessel beam in near fields, as shown in the diamond-shaped overlapping region in Fig. 1. It should be noted that leaky-wave antennas in [15, 16] are uniform, however, in the current work, metasurface is sinusoidally modulated.
The paper is organized as follows. Firstly, we introduce the design flow of holographic meta-
surface for conical beams and its relationship with leaky wave. Then to confirm the direction of
conical beams, a conical beam with 15-degree polar angle is validated by the corresponding ra-
diation patterns from both simulations and measurements. After that, the near field of a smaller
holographic metasurface is scanned to verify the existence of Bessel beam, along with Bessel-
function-like curves of field distributions from both simulations and measurements. Such Bessel
beams may be useful in imaging systems or wireless power transmissions with dynamic focal-
depth controls.

2. Theoretical foundation and the design process

The holographic metasurface composed of modulated surface impedance is actually a peri-
odic leaky-wave antenna accompanied with a perturbation [22]. Hence the radiation condition
for only one spatial harmonic should be chosen when using the holographic metasurface to
shape conical beams. Suppose that the metasurface is located in the x-y plane, where a small
monopole is placed at the center, the distribution of surface impedance for conical beams is
then written as [23]

\[ Z(\rho, \theta) = j[X + M \cos(kn\rho \pm k\rho \sin \theta)], \tag{1} \]

in which \( X \) is an averaged value of inductive reactance, \( M \) is a modulation depth, \( n \) is the effec-
tive index of refraction for surface wave, \( \rho \) is the radial distance, \( k \) is the free-space wavenum-
ber, and \( \theta \) is the polar angle of the conical beam in spherical coordinates. In particular, “−”
represents the forward leaky wave, while “+” denotes the backward leaky wave. As the period
\( p \) of \( Z(\rho, \theta) \) is equal to \( \frac{2\pi}{k(n + \sin \theta)} \) for the backward leaky wave, the first spatial harmonic would
be [17]

\[ k_{-1} = nk - \frac{2\pi}{p} = -k \sin \theta, \tag{2} \]

which means that \(-\theta\) is exactly the polar angle for the holographic design. Since the Bessel
beam could be explained as superposition of all possible plane waves with wave vectors lying
on the surface of a cone, only the conical beams composed of backward leaky waves would
interfere with each other, as illustrated in Fig. 1. From the diamond-shaped overlapping region,
we note that the propagation length of the Bessel beam is \( Z_{\text{max}} = R / \tan \theta \), in which \( R \) is the
radial length of metasurface, or the central spot size of the Bessel beam.

To realize the surface impedance distribution of the metasurface described in Eq. (1), we use
square metallic patches array. A unit cell is illustrated in Fig. 2(a), which is a square metallic
patch based on a 1.57mm-thick substrate with dielectric constant 2.2 and lattice constant \( d \).
Considering that the unit cells of the holographic metasurface are sinusoidally modulated and
the size of adjacent unit cells varied little by little, we set periodic boundary conditions for the
unit cell to calculate the surface impedance, as shown in Fig. 2(b). Changing the gap (\( g = d - a \)
from 0.2 to 1mm, the dispersion diagram between phase and frequency is calculated by using
the Eigenmode Solver in the commercial software, CST Microwave Studio. Note that the phase
is equal to \( k_t d \), where \( k_t \) is the tangential component of wavenumber for the surface wave. From
the dispersion diagram we can determine the tangential wavenumbers \( k_t \) for different \( g \) of the
unit cells at 17GHz. Once \( k_t \) is determined, the inductive surface impedance \( Z \) under transverse
magnetic (TM) surface wave is then calculated by [26]

\[ Z = Z_0 \sqrt{1 - \frac{k_t^2}{k^2}}, \tag{3} \]
Fig. 2. (a) The unit cell of a square metallic patch with the lattice constant \(d = 3\text{mm}\), the patch size \(a\), and the gap between adjacent metallic patches \(g = d - a\). (b) The boundary setting of the unit cell in the CST Microwave Studio. (c) Curve fitting for \(g(Z)\) after getting different value of surface impedance \(Z\) in 17GHz by changing \(g\) from 0.2mm to 1mm in (b).

where \(Z_0\) is the impedance of free space. Similarly, the effective refractive index \(n\) for different unit cells will be calculated from the relationship \(n = k_t/k = \sqrt{1 - (Z/Z_0)^2}\), where \(k\) is the free-space wavenumber at the working frequency 17GHz. For the averaged value of inductive reactance \(Z = jX\), we have \(n = \sqrt{1 + (X/Z_0)^2}\).

In the simulation, a series of \(Z\) from \(\text{min}(|Z|) = 245.70\Omega\) to \(\text{max}(|Z|) = 163.38\Omega\) at 17GHz is calculated when \(g\) changes from 0.2mm to 1mm with a step size of 0.1mm. The relationship between \(g\) and \(Z\) for different patches is shown in Fig. 2(c) by curve fitting. The function \(g(Z)\) is given by

\[
g = (-1.3360 \times 10^{-6})|Z|^3 + (9.2688 \times 10^{-4})|Z|^2 - 0.2189 \times |Z| + 17.84,
\]

which can be used to calculate the sizes of metallic patches quickly. For covering all the surface impedances ranging from \(\text{min}(Z)\) to \(\text{max}(Z)\), we let the averaged value of inductive reactance \(X = (\text{max}(|Z|) + \text{min}(|Z|))/2, M = (\text{max}(|Z|) - \text{min}(|Z|))/2\), and then the effective index of refraction \(n = \sqrt{1 + (X/Z_0)^2}\) can be obtained. Finally, we get \(X = 204.54, M = 41.16\) and \(n = 1.1377\).

We have calculated surface impedance of metasurface by solving the dispersion diagram [26], which is accord with the impedance boundary condition [27, 28] as analyzed in [24]. Another alternative method, the generalized sheet transition conditions (GSTC) can also be used to analyze the surface impedance [29]. Here, since the simulation and calculation of dispersion diagram is accurate enough, equation (4) is used in following simulation verifications.

3. Simulation and measurement results

3.1. Ensure the direction of conical beam with far field pattern

By combining Eq. (1) and Eq. (4), we can realize a holographic metasurface with the backward leaky waves of polar angle \(\theta = 15^\circ\), as demonstrated in Fig. 3(a). The fabricated holographic metasurface is based on a commercial substrate (F4B) with the dielectric constant 2.2 and tangent loss 0.001. The upper surface is covered with differently-sized metallic square patches to form the holographic pattern, which has a size of 408mm×408mm in the x-y plane. The TM surface waves are generated by a monopole using a SubMiniature version A (SMA) connector in the center of the metasurface.
To ensure the desired polar angle $\theta = 15^\circ$ for conical beams at 17 GHz, the corresponding normalized two-dimensional (2D) radiation patterns of the metasurface by both numerical simulations and measurements are illustrated in Figs. 3(b) and 3(c), respectively. In the simulations, the main lobe has a polar angle around $17^\circ$ at 17 GHz, which shows good agreements with the desired polar angle $\theta = 15^\circ$. The polar angle changes to $20^\circ$ at 16.5 GHz and $14^\circ$ at 17.5 GHz, showing the beam scanning characteristics of backward leaky waves. The side-lobe level (SLL) is about -13.22 dB, which ensures that the edge diffraction is small since the leaky waves decay exponentially along the surface due to the leakage loss. In the experiments, the holographic metasurface was fixed on a 2D rotating platform in the anechoic chamber, in which the x-z plane corresponds to the horizontal plane and a 360-degree horizontal radiation pattern can be measured. Figure 3(c) shows the measurement result with SLL under -10dB, which coincide with the simulation results very well except a slight asymmetry due to the surface flatness problem of fabricated metasurface.

From above discussion, we have demonstrated that the backward leaky waves in circular symmetry could be designed along the pre-appointed polar angle. The beam scanning characteristics also confirms the leaky waves radiate in the backward direction. The conical beam in the far-field region could be used in frequency-scanning antennas [18–21]. Here the main focus is to illustrate the Bessel beams interfered by the conical beams (or the backward leaky waves) in the near-field region. The maximum measurement range in experiments for near-field is limited in an maximum area of 200mm $\times$ 200mm. In numerical simulation, for a holographic metasurface with an area of 408mm $\times$ 408mm and a polar angle $\theta = 15^\circ$, the mesh generation for numerical simulations would be more than 400 million while the computer memory and the computing time are all limited. So we design and fabricate a smaller holographic metasurface to verify the Bessel Beam in near field. The smaller metasurface has an area of 254mm $\times$ 254mm and a polar angle $\theta = 45^\circ$ for the radiation conical beams. The propagation length of corresponding Bessel beam is $Z_{\text{max}} = R / \tan \theta = 126 / \tan 45^\circ = 126$mm at 17 GHz. Thus the smaller metasurface with bigger polar angle has a smaller area of $2R \times Z_{\text{max}}$ for the near field to monitor in CST simulations, and a mesh number, about 60 million. Meanwhile, it is also suitable for measurements in a 2D near-field microwave scanning system having a measurement area of 200mm $\times$ 200mm, as illustrated in Fig. 1, the Bessel-beam region is included in a smaller area of $R \times Z_{\text{max}}$. 

Fig. 3. (a) A portion of the fabricated holographic metasurface with the size of 408mm $\times$ 408mm to generate the backward conical beam at $\theta = 15^\circ$. (b) The corresponding 2D radiation patterns simulated by CST. (c) The corresponding 2D radiation patterns by measurements.

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3.2. Verifying the Bessel beams in near field

To verify the phenomena of Bessel beams with beam scanning characteristics, a region from \( z = 0 \) to \( z = 252 \text{mm} \) in the x-z plane are monitored for the z-components of electric fields (\( |E_z| \)) by CST Microwave Studio, and the simulation results are demonstrated in Figs. 4(a)-4(c) for 16.5, 17, and 17.5GHz, respectively, in which a narrow pseudo-Bessel beam in the center along the normal direction of the metasurface is clearly observed by interference of backward leaky waves.

Fig. 4. The \( |E_z| \) distributions in the near-field region (from \( z = 0 \) to \( z = 252 \text{mm} \) in the x-z plane) of the holographic metasurface. The metasurface is located in the x-y plane with the size of 252mm \( \times \) 252mm, where a pseudo-Bessel beam above the x-y plane is interfered by the backward leaky waves with \( \theta = 45^\circ \). (a)-(c) The simulation results at 16.5, 17 and 17.5GHz. (d)-(f) The measurement results at 16.5, 17 and 17.5GHz. We remark that the measurement area is limited in a size of 200mm \( \times \) 200mm due to the experiment constraint, which is also marked in (a)-(c) with dashed lines. In (b) and (e), the non-diffraction range is drawn in solid lines. The propagation distance of pseudo-Bessel beam is changed due to the beam scanning characteristics of backward leaky waves.

Meanwhile, the normalized near-electric-field distributions at the same frequencies are measured in the 2D near-field microwave scanning system. An automatically controlled 2D translation stage has been used to scan the maximum area of 200mm \( \times \) 200mm in the x-z plane. As shown in Fig. 5(a), the holographic metasurface is fixed upon the 2D translation stage which moves in the x-z plane. The fabricated metasurface has the same size as that in simulations. To generate the TM surface wave and leaky waves, a SMA connector is welded in the center of metasurface as a monopole. To measure the near fields of the pseudo-Bessel beam, a small monopole probe along the z direction is fixed before the metasurface, and connected through a coaxial cable. The probe is composed of an extending section of copper core. To measure the z-components of electric fields, the extending section was bent toward the z direction while the coaxial cable was still fixed along the x direction. Both the SMA connector and probe are connected to the Agilent vector network analyzer (N5230). As the holographic metasurface moves in the x-z plane by the 2D translation stage, the electric fields \( |E_z| \) in the near-field region over an area of 200mm \( \times \) 200mm are measured by the probe.
The measured electric field distributions are illustrate in Figs. 4(d)-4(f) at 16.5, 17, and 17.5GHz. Comparing with Figs. 4(a)-4(c), we observe very good agreements between the simulated and measured results. The propagation distance of the pseudo-Bessel beam varies when the frequency changes, which is due to the beam scanning characteristics of leaky-waves. The dynamic focal-depth control provides a promising option in applications, as discussed in details later. At 17GHz, Figs. 4(b) and 4(e) show a propagation length of about 126mm along the z axis in a diamond-shaped area, which is consistent with the radial length of 126mm along the x axis as $\theta = 45^\circ$ (see Fig. 1).

To verify the Bessel-like distribution in the transverse cross section of the diamond-shaped area in Figs. 4(b) and 4(e), the normalized $|E_z|$ distributions at 17GHz along a line from $x = -63$mm to $x = 63$mm in the x-z plane ($y = 0, z = 63$mm), are extracted and plotted in Fig. 5(b), for both simulations and measurements. From Fig. 5(b), we observe clearly the Bessel-like distribution in the transverse direction.

The above simulated and measured results demonstrate that spatial Bessel beams could be generated by the holographic metasurface. Bessel beam with a focus depth of 126mm is generated at 17GHz by setting $R = 126$mm and $\theta = 45^\circ$ as illustrated. A larger propagation distance of Bessel beam could also be generated, by using a bigger holographic metasurface with a smaller polar angle, for example, $\theta = 15^\circ$. The feasibility has been proved by the radiation patterns as shown in Figs. 3(a)-3(c).

Comparing with the Bessel beams in the millimetre waves (30-300GHz) and terahertz frequencies (300GHz-1THz) generated by utilizing quasi-optical property [4, 6–8, 39–41], the Bessel beams in microwave (1-30 GHz) are usually analysed with distribution of electromagnetic fields due to low frequency [11–13, 15, 16]. The focal depth of the proposed Bessel beam could be changed by frequency due to leaky-wave characteristics. The exponential decay of leaky-waves could be described by an attenuation constant, if the leaky-waves decay to a negligible value more quickly, Bessel beams will be produced in a smaller diamond-shaped area, and vice versa.

The proposed Bessel beams in the radio frequency may be used in the imaging systems [30–33], detection [13], and wireless power transmissions [34]. The dynamic focal-depth control may be useful in some dynamic focusing imaging case [35], or adaptive scanning imaging with sweeping frequency in detecting irregular objects [36–38].
4. Conclusion

In summary, the holographic metasurface is used to generate spatial Bessel beams in the microwave frequency, and the leaky-wave characteristics of the Bessel beams are analysed. Both numerical simulations and experiments verify the feasibilities. The generation of Bessel beams in the microwave frequency with dynamic focal-depth control may provides more freedom in application of the near-field probing, wireless power transmission, and medical imaging.

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