Miniaturized Wideband Metasurface Antennas

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Abstract—A single-layer tightly-coupled metasurface with narrow gaps in between and a dual-layer metasurface with feasible wide gaps are proposed to realize the miniaturization of a low-profile wideband antenna, respectively. The single-layer metasurface consists of one square patch array while the dual-layer metasurface is composed of two square patch arrays. Both the single-layer and dual-layer metasurfaces supported by grounded dielectric substrate are considered as waveguided metamaterials to retrieve the effective refractive index along the propagation direction. The effective propagation constant is subsequently derived to initially estimate the resonant frequencies of the dual-mode antenna. Both the single-layer metasurface with narrow gap and the dual-layer metasurface exhibit increased effective propagation constant and therefore achieve the antenna miniaturization. Both types of antennas are able to produce the realized gain greater than 6.5 dBi over the wide impedance bandwidth of 27% with a reduced radiating aperture size of 0.46λ₀ × 0.46λ₀ and a thickness of 0.06λ₀ (λ₀ is the free-space wavelength at the center operating frequency of 5.5 GHz).

Index Terms—Wideband antenna, low-profile antenna, miniaturization, waveguided metamaterial, metasurface, effective medium theory.

I. INTRODUCTION

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ONVENTIONAL broadband microstrip patch antenna techniques usually require electrically-thick and low-permittivity dielectric substrate (typically 0.1λ₀-thick air-substrate for about 30% fractional bandwidth), such as the utilization of capacitive probe feed, L-probe feed, aperture coupling, U/E-slotted patch, and stacked patches [1]–[6]. Meanwhile, the investigation and demonstration of exotic electromagnetic properties of metamaterials artificially constructed of periodic sub-wavelength cells have profoundly influenced physical and engineering research since the year of 2000 [7]–[10], in particular, have opened a new window for designing innovative antennas with improved performance. For instance, the composite right/left-handed (CRLH) metamaterials have been widely applied in antenna designs because of their unique dispersion characteristics [10]. With deep analysis and understanding of the rich dispersion characteristics and the operating modes of the metamaterial structures, we have successfully proposed and developed a new class of metamaterial-based low-profile broadband antennas with consistent directional boresight radiation by exciting two adjacent resonant modes over the desired frequency ranges [11]–[13]. The aforementioned limitations of the existing broadband microstrip patch antenna techniques have been alleviated using developed metamaterial-based antenna techniques, wherein the wide operating bandwidth with high efficiency has been achieved with a thin substrate of relatively high dielectric constant, typically 0.06λ₀-thick substrate with a dielectric constant around 3.55 for achieving 30% fractional bandwidth. The wideband low-profile metasurface antenna proposed in [13] has been further developed by other groups to realize low-profile broadband antennas with filtering function [14] and circular polarization [15].

Besides the achieved performance, it is noted that the radiating aperture of the previous metasurface antenna is as large as 0.7λ₀ × 0.7λ₀ with a substrate having a dielectric constant around 3.55 [13], [15]. The antenna aperture size will be further enlarged if a substrate with a lower dielectric constant is used. The higher-permittivity substrate can be used to reduce the antenna aperture size at a price of reduced bandwidth and radiation efficiency. However, a small inter-element spacing is usually required in array configuration for low sidelobe levels (SLLs) and suppressed grating lobes. The inter-element spacing is also a key consideration for wide scanning phased array antennas. A smaller inter-element spacing results in a smaller inter-element phase difference for scanning the beam to a wide angle, such that low SLLs and good axial ratios could be maintained and the occurrence of the grating lobes would be avoided within the wide-angle beam steering. In this case, antenna miniaturization is even more critical to achieve low mutual coupling within a small inter-element spacing [16], [17]. Meanwhile, miniaturization of wideband antenna is increasingly demanded in compact wideband multiple-input multiple-output (MIMO) antenna systems for modern communications [18]–[20]. As a result, the wideband antenna element with further miniaturized size (e.g., 0.5λ₀ × 0.5λ₀) is highly desired in high-performance wideband fixed/phased array antennas and compact wideband multiple antenna systems. More recently, a metasurface inspired printed
antenna embedded in a half-wavelength square cavity was proposed for reaching a large fractional –10-dB bandwidth around 30% but with a large thickness up to 0.15λ0 [21].

In this paper, we propose two ways to miniaturize the low-profile wideband metasurface antennas for potential applications in high-performance wideband fixed/phased array antennas and compact wideband MIMO antenna systems. First, a low-profile single-layer metasurface antenna (SIMA) with narrow gaps in between the metasurface patch array elements is investigated for potential antenna miniaturization while maintaining wideband performance. Then, a wideband miniaturized low-profile dual-layer metasurface antenna (DUMA) is proposed and studied with wider gaps between the metasurface patch array elements to facilitate the fabrication. Both the single-layer and dual-layer metasurfaces working together with the supported grounded substrate are considered as the waveguided metamaterials to extract the effective refractive index [22], [23]. The effective propagation constant is then derived to estimate the resonant frequencies of the TM00 and antiphase TM20 modes of the antenna [13]. The wideband performance of the proposed miniaturized low-profile dual-layer metasurface antenna is verified by the measurement results, which are in good agreement with the simulation results by using CST Microwave Studio [24].

II. MINIATURIZED SINGLE-LAYER TIGHTLY-COUPLED METASURFACE ANTENNA

The low-profile single-layer tightly-coupled metasurface antenna is revisited to study the potential for size miniaturization. As shown in Fig. 1, the single-layer metasurface is composed of a 4×4 square patch array with a periodicity of p and a narrow gap width of g, printed on the top surface of a grounded substrate with a thickness of h1. The antenna is fed by a 50-Ohm microstrip line implemented on the bottom substrate of thickness h0 through a rectangular aperture cut on the ground plane. The Rogers RO4003C substrate (εr = 3.55, tan δ = 0.0027) is utilized for all the antennas throughout the paper.

Fig. 1. Configuration of the single-layer tightly-coupled metasurface antenna.

The single-layer metasurface working together with the grounded substrate is regarded as a waveguided metamaterial. Fig. 2(a) depicts the simulation model with the applied boundary conditions and TEM wave excitations, wherein two metasurface unit cells are loaded in the upper metal plate of the planar waveguide. Since the period of the metasurface unit cell is much smaller than the operating wavelength within the frequency band of interest, the volume occupied by the metasurface in the planar waveguide can be taken as an effective medium. The effective medium parameters are obtained from the simulated reflection and transmission coefficients and the subsequent standard retrieval process [25]. The retrieved y-components of the refractive indexes of the metasurface waveguided metamaterial with different metasurface gap widths are compared in Fig. 2(b). With the

![Simulation model for extracting the effective medium parameters](image1.png)

![Retrieved effective refractive index](image2.png)
unchanged dimensions of \( p = 7.05 \text{ mm} \) and \( h_1 = 3.25 \text{ mm} \), the metasurface with a narrower gap width of \( g = 0.25 \text{ mm} \) exhibits

the higher effective refractive index and a lower effective extinction coefficient.

The effective propagation constant is derived from the refractive index to estimate the dual-mode frequencies of the antenna using the same empirical equations in [13], which are reproduced as follows:

\[
\beta_p / \pi = (1 - 2\beta_r \Delta L / \pi) / 4, \quad \text{TM}_{10} \tag{1}
\]

\[
\beta_p / \pi = (1 - 2\beta_r \Delta L / \pi) / 2, \quad \text{antiphase TM}_{20} \tag{2}
\]

\[
\beta_r = 2\pi f \sqrt{\varepsilon_r} / c \tag{3}
\]

\[
\Delta L / h_1 = 0.412 \left( \frac{\varepsilon_r + 0.3}{\varepsilon_r - 0.258} \right) \left( \frac{4p}{h_1} + 0.262 \right) \left( \frac{4p}{h_1} + 0.813 \right) \tag{4}
\]

\[
\varepsilon_r = \frac{1}{2} + \frac{\varepsilon - 1}{2} \left( 1 + 3h_1 / p \right)^{-1/2} \tag{5}
\]

where \( f \) is the operating frequency, \( c \) is the speed of light in vacuum, \( \beta_p \) is the effective phase constant of the metasurface waveguided metamaterial, and \( \beta_r \) is the phase constant in the effective extended region with a length of \( \Delta L \) at each end of the antenna along the resonant direction (i.e. along y-axis) due to the effect of the fringing fields.

The derived propagation characteristics of the single-layer metasurface waveguided metamaterial are presented in Fig. 2(c). The dual-mode resonant frequencies of the metasurface with \( g = 0.25 \text{ mm} \) are initially calculated to be 5.1 GHz and 6.35 GHz, lower than 5.36 GHz and 6.63 GHz of the metasurface with \( g = 0.5 \text{ mm} \), respectively. The simulated reflection coefficient and gain of the single-layer metasurface antennas are plotted in Fig. 3. The matching frequencies of the antenna are found to be 5.08 GHz and 6.14 GHz for SIMA I, and 5.58 GHz and 6.60 GHz for SIMA II, close to the estimated resonant frequencies from the analysis of the propagation characteristics. With the decrease of the gap width from \( g = 0.5 \text{ mm} \) to \( g = 0.25 \text{ mm} \), the 

-10-dB reflection coefficient frequency band of the single-layer metasurface antenna has been downward shifted from 5.16–6.86 GHz to 4.71–6.38 GHz. The single-layer tightly-coupled metasurface antenna SIMA I with a narrow gap width of 0.25 mm is able to produce 30\% fractional bandwidth with a low profile of 0.06\( \lambda_0 \) and a miniaturized aperture area of \( 0.51\lambda_0 \times 0.51\lambda_0 \). The simulated realized gain varies from 6.5 dBi to 8.0 dBi and the radiation efficiency is higher than 90\% over the wide operating bandwidth. The antenna miniaturization is achieved due to the increased effective refractive index caused by the reduced metasurface gap width.

III. MINIATURIZED DUAL-LAYER METASURFACE ANTENNA

A. Design

The configuration of the proposed wideband miniaturized dual-layer metasurface antenna and the corresponding Cartesian coordinate system are shown in Fig. 4. A 4\x4 square patch array with a periodicity of \( p \) and gap width of \( g \), and a 6\x6 square patch array with a periodicity of \( p_t \) and gap width of \( g_t \), are separately printed onto the top and bottom surface of a piece of thin substrate with a thickness of \( h_2 \) to form the dual-layer metasurface. The antenna substrate has the same overall thickness of \( h_1 \).

The dual-layer metasurface supported by the grounded substrate is considered as a waveguided metamaterial. Its effective medium parameters are extracted using the simulation model shown in Fig. 5(a), wherein the 2\x2 upper patch cells and 3\x3 lower patch cells of the dual-layer metasurface are incorporated in the planar waveguide as the relation between the two periodicities is set as \( 2p = 3p_t \). The dimensions of the dual-layer metasurface of the antenna (DUMA I) are as follows: \( p = 7.05 \text{ mm}, \quad g = 0.6 \text{ mm}, \quad p_t = 4.7 \text{ mm}, \quad g_t = 1.6 \text{ mm}, \quad h_2 = 0.508 \text{ mm}, \quad h_1 = 3.25 \text{ mm} \). The retrieved y-component of the refractive index of the dual-layer metasurface waveguided metamaterial in DUMA I is presented in Fig. 5(b) in comparison with that of the single-layer tightly-coupled metasurface in SIMA I. In

![Fig. 3. |S11| and realized boresight gain of the single-layer metasurface antennas.](image)

![Fig. 4. Configuration of the dual-layer metasurface antenna.](image)
order to achieve the same high effective refractive index for antenna miniaturization, the gaps in the dual-layer metasurface can be much wider than those in the single-layer metasurface. From the derived effective propagation characteristics given in Fig. 5(c), the two resonant mode frequencies of DUMA I are initially predicted to be 5.13 GHz and 6.27 GHz using the empirical equations (1)–(5).

Fig. 6 shows the simulated reflection coefficient and realized boresight gain of the DUMA I. The matching frequencies of the DUMA I are 5.09 GHz and 5.92 GHz, close to the prediction from the mode analysis. The proposed DUMA I with a radiating aperture area of 0.51λ₀ × 0.51λ₀ achieves an operating bandwidth of 27% (4.70–6.17 GHz) with $|S_{11}| \leq -10$ dB, realized boresight gain varying from 6.5 dBi to 7.8 dBi, and radiation efficiency higher than 90%.

Fig. 7 depicts the simulated electric field distributions in the cross-section of the proposed dual-layer metasurface antenna at the frequencies of 5.09 GHz and 5.92 GHz. It indicates that the conventional $TM_{10}$ and antiphase $TM_{20}$ modes remain in the dual-layer metasurface give rise to the increase of the effective refractive index, and consequently the antenna miniaturization.

B. Miniaturization

The miniaturization potential of the proposed wideband dual-layer metasurface antenna is further discussed in this subsection. To realize a wide bandwidth centered at ~5.5 GHz with a smaller periodicity of $p = 0.3$ mm, the metasurface gaps of DUMA I are optimized to be $g = 0.3$ mm and $s = 1.2$ mm to create the DUMA II as well as $g = 0.14$ mm SIMA III for the required high effective refractive index.

The retrieved propagation characteristics are compared in Fig. 8(a). Fig. 8(b) shows the simulated $|S_{11}|$ and gain of the antennas DUMA II and SIMA III with a radiating aperture area of 0.46λ₀ × 0.46λ₀. The dual-layer metasurface antenna DUMA II achieves an operating bandwidth of 27% (4.76–6.29 GHz) for $|S_{11}| \leq -10$ dB, realized boresight gain varying from 6.5 dBi to 7.5 dBi, and radiation efficiency higher than 90%. The single-layer SIMA III exhibits almost the same impedance bandwidth and gain as the dual-layer DUMA II. However, the minimum gap width in SIMA III is only 0.14 mm against 0.3 mm in DUMA II. The gaps of SIMA III, 0.14 mm in width, are too small to fabricate using the standard PCB process while the antenna performance is quite sensitive to fabrication tolerance of the gaps.

Furthermore, the proposed wideband dual-layer metasurface antenna can be miniaturized by reducing the substrate thickness $h_2$ as well. When printed onto a thinner substrate, the dual-layer
metasurface waveguided metamaterial generates a higher effective refractive index for the size reduction of the antenna.

Therefore, the proposed dual-layer metasurface is much more promising for achieving a wideband miniaturized low-profile antenna operating at higher frequency bands, by considering the miniaturization ability and ease of fabrication.

IV. EXPERIMENTAL VALIDATION

To verify the proposed dual-layer metasurface antenna design, DUMA I was fabricated with slight changes without loss of validity. The variation of the lower layer of the dual-layer metasurface is illustrated in Fig. 9(a). The 6×6 square patch array is separated in the middle with a larger center gap width of gc = 2 mm. The other modified dimensions are as follows: p = 7 mm, g = 1 mm, gc = 0.8 mm, Lc = 20 mm, s = 11.5 mm. The occupied aperture area of the fabricated dual-layer metasurface antenna is 27.4 mm × 28.6 mm, or 0.50λ0 × 0.52λ0 at the center operating frequency of 5.5 GHz. An additional transition from the grounded coplanar waveguide (GCPW) to microstrip line (MSL) is introduced to the prototype as shown in Fig. 9(b). The designed GCPW-to-MSL transition has a wide bandwidth of 4.5–6.5 GHz at −35-dB reflection coefficient with the insertion loss better than 0.15 dB.

Fig. 9(c) compares simulated and measured |S11| and realized boresight gain of the dual-layer metasurface antenna. The simulated bandwidth of the antenna with −10-dB reflection coefficient is 24.4% (4.82–6.16 GHz) while the measured one is 24.5%, from 4.86 to 6.22 GHz with slight frequency shift. The simulated realized boresight gain varies from 6.5 dBi to 7.8 dBi with radiation efficiency higher than 88% over the

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**Fig. 8.** (a) Propagation characteristics and (b) simulated |S11| and realized boresight gain of the single-layer and dual-layer metasurface antennas. (DUMA II: p = 6.3, g = 0.3, p1 = 4.2, gs = 1.2, h2 = 0.508, h1 = 3.25, hs = 0.813, Wn = 1.8, L = 20.5, W = 0.3, s = 10.3, Lc = 40; SIMA III: p = 6.3, g = 0.14, h1 = 3.25, h0 = 0.813, Wn = 1.8, L = 20.5, W = 0.3, s = 10.2, Lc = 40. unit: mm)

**Fig. 9.** Dual-layer metasurface antenna: (a) variation of the lower layer of the metasurface, (b) photos of the antenna prototype, (c) simulated and measured |S11| and realized boresight gain. (p = 7, g = 1, p1 = 4.7, gc = 0.8, gc = 2, Lc = 20, s = 1.5, unit: mm)

**Fig. 10.** Simulated and measured normalized radiation patterns in E/H-planes at 5.0, 5.4, and 6.0 GHz.
impedance bandwidth. The measured and simulated gains are in good agreement with a maximum gain drop of 0.9 dB at 5.3 GHz. Fig. 10 plots the measured and simulated normalized radiation patterns at the operating frequencies of 5.0, 5.4, and 6.0 GHz. Over the operating band, the simulated front-to-back ratio (FBR) is greater than 11 dB and up to 18 dB at 5.4 GHz, and the 3-dB beamwidth is $69^\circ\pm10^\circ$ in $E$-planes and $69^\circ\pm7^\circ$ in $H$-planes, all in good coincidence with the measurements. Within the 3-dB beamwidth, the cross polarization levels are simulated to be less than $-37$ dB in $H$-planes and negligible in $E$-planes, while the measured are less than $-28$ dB and $-23$ dB in $H$- and $E$-planes, respectively.

V. CONCLUSION

The wideband low-profile single-layer and dual-layer metasurface antennas have been proposed for miniaturization. Both the single-layer and dual-layer metasurfaces working together with the supported grounded dielectric substrate have been considered as the waveguided metamaterials to extract the effective refractive index for estimating the resonant frequencies of the antennas. The antenna miniaturization has been achieved with the increased effective refractive index, resulted from the narrowed gaps of the single-layer metasurface and the enhanced capacitive couplings of the dual-layer metasurface, respectively. Both single-layer and dual-layer metasurface antennas with the respective minimum gap width of 0.14 mm and 0.3 mm are able to obtain the realized gain greater than 6.5 dBi over the wide impedance bandwidth of 27% with a reduced radiating aperture size of $0.46\lambda_0 \times 0.46\lambda_0$ and a low profile of $0.06\lambda_0$ ($\lambda_0$ is the free-space wavelength at center operating frequency of 5.5 GHz). The miniaturized single-layer tightly-coupled wideband metasurface antenna is more suitable for working at low frequency ranges due to the simpler structure, while the miniaturized dual-layer wideband metasurface antenna for the high frequency operation wherein feasible wide gaps are much preferred. The proposed wideband miniaturized low-profile antennas would be promising for various communication systems, such as high-performance wideband fixed array antennas, high-performance wideband wide-scanning phased array antennas with either linear or circular polarization, and compact wideband MIMO antenna systems.

REFERENCES