Low-Profile Unidirectional Microstrip-Fed Slot Antenna Using Metasurface

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Abstract—A new design for a microstrip-fed slot antenna (MFSA) is proposed and developed for improving bandwidth, gain and reducing back radiation. In contrast with most uni-directional MFSA, a metasurface as a superstrate is employed to reduce the back-lobe radiation and enhance the gain without a metal reflector. The metasurface exhibits the near-zero permeability ($\mu < 1$) and negative reflection phase. Design considerations for the proposed structure are given, and the design is validated by measurements. The measured radiation patterns show that the proposed structure can offer a high radiation efficiency, a good front to back radiation ratio, and a high co-cross polarization ratio. Due to the negative reflection phase of metasurface, the overall thickness of the proposed antenna is only 9.9 mm, which corresponds to $\lambda_0/12$ at center frequency of 2.45 GHz.

I. INTRODUCTION

Microstrip-fed slot antennas (MFSAs) are widely used as radiating element due to its low profile, light weight and low-cost. A single layer MFSA naturally radiates bidirectionally, this characteristic is necessary for some applications, such as antennas for roads. However, this inherent bidirectional radiation is undesired in some wireless communication applications such as in base station antenna. Several methods for reducing the back radiation and improving the gain of slot antennas have been proposed [1]-[2]. Two common approaches are to add an additional metal reflector [1] and an enclosed cavity [2] underneath the MFSA to redirect radiated energy from an undesired direction. Usually, the metal conductor or cavity has to be placed a quarter wavelength ($\lambda/4$) away from the MFSA, making the overall size of the antenna too big and bulky for low frequency range of operations. Although these additionally attached layers can reduce or eliminate back radiation, impedance matching and radiation pattern performances are degraded due to the surface wave induced on the metal back plane. It allows the propagation of parallel plate waveguide modes to a great distance along the surface of a metal reflector when it reaches the edges of the reflector, it radiates. Also, the use of an enclosed cavity can excite higher order modes.

Recently, metamaterial is used to load the microstrip patch antennas as superstrate and substrate to enhance the bandwidth, gain, directivity as well as to achieve miniaturization [3]-[6]. Especially, use of the metasurface as a superstrate has been studied due to ease to fabricate and take less space than their 3-D metamaterial counterparts. Metasurface is the 2-D planar equivalent of metamaterials that exhibit anomalous values in their constitutive parameters at certain frequencies. However, most of them are designed for directional antenna especially microstrip patch antenna. For the slot antennas, usually, the electromagnetic bandgap (EBG) is used [7]-[8].

This paper is extended to practical bi-directional to unidirectional antenna by the metasurface operating at WiMAX (2.3 GHz) and WLAN (2.45 GHz) frequency bands. The objective of this paper is to present a metasurface superstrate, composed of square loop resonators (SLRs) to load the MFSA to enhance its bandwidth, gain, and to reduce the back radiation. The metasurface placed very close to a slot radiator ($0.061\lambda_0$) to manipulate its radiation pattern instead of using a conductor-back reflector ($\lambda_0/4$), so the proposed antenna is a subwavelength format. Simultaneously, the impedance bandwidth and level of cross polarization are also improved.
II. ANTENNA STRUCTURE AND ITS OPERATION MECHANISM

Fig. 1 depicts the geometrical layout, metasureface and 3D view of the proposed antenna. To reduce the back radiation from the slot and increase bandwidth, a metasurface is placed atop the slot with air gap of $h_c$. A narrow rectangular slot is cut on the ground plane as the radiating element and the microstrip line feeder is etched on the other side. A slot with length $L_s$ and width $W_s$ is located at the center of a square ground plane of 108 mm $\times$ 108 mm. The slot antenna is fed with a 50-$\Omega$ ($W_f = 3.0$ mm) open circuited microstrip line. To get good matching, it is provided by varying the feed line length ($L_f$).

For the metasurface as shown in Fig. 1(b), it comprises of an array 4 $\times$ 4 square loop resonators (SLRs). The unit cell has a square periodicity of $P = 20$ mm and the width of loop is 1 mm and gap between loops is all represented of 2 mm. The average cell size of SLR unit cell is smaller than $\lambda_g/4$ which satisfies the condition of effective homogeneity [6]. It can control the phase of the wave, which is reflected at the surface. A detailed explanation of the physical phenomena behind this structure can be found in [4]-[5] and [9]. This metasurface exhibits a mu-near-zero (MNZ- $0 < \mu < 1$)

III. RESULTS AND DISCUSSION

To further certify the validity of the design, the proposed antenna was fabricated and tested as shown in Fig. 2. The slot antenna was fabricated on an inexpensive FR-4 substrate with a dielectric constant of $\epsilon_r = 4.2$, a thickness of 1.6 mm, and a loss tangent of $\tan \delta = 0.02$. The metasurface structure is formed by using a FR-4 dielectric slab with a thickness of 0.8 mm and a dielectric constant $\epsilon_r = 4.2$. The simulated and measured results are illustrated and compared. The simulated and measured reflection coefficient curves of the loaded (with metasureface) and unloaded (with metasureface) slot antennas are shown in Fig. 3. It is clearly seen that the unloaded slot antenna has only a single resonant mode at 2.45 GHz with a good matching impedance. Comparison of the bandwidths is shown in Fig. 3; the bandwidth is increased from 8% (2.35-2.55 GHz) for the unloaded slot antenna to 23% (2.14-2.70 GHz) for the loaded slot antenna with metasurface. For the loaded slot antenna with metasurface, however, two resonant modes at 2.225 GHz and 2.525 GHz, are excited. The two excited modes are associated to the loaded slot antenna by metasurface (first resonance) and cavity effect (second resonance), which is to put metasurface on the top of ground plane so as to form a flat-plate cavity [4], and this characteristic leads to enhance impedance bandwidth. From the results, the $-10$ dB $|S_{11}|$ is from 2.14-2.70 GHz (measured) and 2.14-2.65 GHz (simulated). The obtained measurement confirms the wideband characteristic of the proposed design predicted by the simulation. The differences between measured and simulated results could be mainly due to the fact that the antenna is sensitive to the variation of the air gap ($h_c$), which is subject to alignment errors in fabrication process.

To accurately design the proposed antenna for practical applications, its operating principles should be studied carefully. The performance of the proposed antenna structure shows greater sensitivity to variation in some parameters. A parametric study of these parameters presented below provides a useful evaluation of their effects on antenna performance. The two important parameters including the height of air gap ($h_c$) and length of slot ($L_s$) are set as variable and their effects on the impedance bandwidth are studied. These parameters, which have a profound effect on the coupling between the slot and metasurface, allow for the antenna’s input impedance to be adjusted and good matching to be achieved. Fig. 4 shows the simulated reflection coefficients of the proposed antenna with different length of slot ($L_s$). With $W_s = 3$ mm, $L_f = 1$ mm, and $h_c = 7.5$ mm, the slot length $L_s$ is varied from 30 mm to 35 mm. Increasing the slot length will increase the inductance because the diversion of surface current around the slots will be more intensive. Hence, the frequency of the first
resonant mode decreases, as shown in Fig. 4. However, all case has the first resonant frequency lower than the unloaded slot resonance at 2.45 GHz (see Fig. 3) due to the slot antenna is loaded by the metasurface.

Next, the effect of changing air gap $h_c$ is studied as shown in Fig. 5. As shown in Fig. 5, the distance between slot antenna and metasurface mainly affects the frequency corresponding to the upper edge of the bandwidth, whereas it has minimal effect on the frequency corresponding to the lower edge. The second resonant mode may be tuned to a frequency higher than 2.7 GHz, but the $S_{11}$ between the two resonant frequencies will be poorer than -10 dB and unable to meet the desired bandwidth specification.

Radiation characteristics of the proposed antenna have also been studied and measured in an anechoic chamber at three frequencies in two principal planes as shown in Figs. 6 and 7. It can be observed that placed atop by the metasurface, the slot antenna radiates in broadside unidirection instead of bidirectional radiation. As expected, a front-to-back radiation ratio of 15 dB can be achieved for all frequencies. The cross polarization level was also measured; it is more 20 dB lower than the corresponding co-polarization level in both planes. Furthermore, the realized gains of the CPW-fed slot antenna with and without the metasurface were measured as shown in Fig. 8. The gain for absence metasurface is about 1.5 dBi, whereas the presence metasurface can increase to 9.0 dBi at the center frequency. An improvement in the gain of 7.5 dB has been obtained. It is obtained that the realized gains of the present metasurface are all improved within the operating bandwidth. Finally, the antenna efficiency was also measured to be 80 at the center frequency $f = 2.45$ GHz.

For the proposed structure, the electromagnetic waves radiated by the slot antenna at its resonant frequency are confined into the metasurface through magnetic coupling. The key idea behind this configuration is that when the metasurface is illuminated by a primary source tuned to the resonant frequency of the metasurface, the radiated field is spread over a larger radiating aperture enhancing its gain. Alternatively, directive enhancement can be explained by using the theory of effective aperture area—a larger effective aperture area emits a higher maximum directivity. The normalized electric field distributions of the microstrip-fed slot antenna with and without metasurface are shown in Fig. 9. It can be seen that the unloaded metasurface has only one radiating slot, whereas the loaded metasurface has an equivalent of the five slots, which results in a much wider effective area than the absent metasurface. When the metasurface is placed atop of the slot antenna, the power radiated by the antenna is picked up by the metasurface, confined over a larger area on top of the antenna and re-radiated producing an enhancement of the boresight radiation and a reduction of the back radiation.

IV. CONCLUSION

Instead of using a metal reflector, a metasurface as a superstrate is applied to modify the radiation pattern and enhance the antenna gain. It is not only enhanced the radiation characteristics but also the bandwidth is wider. The proposed antenna presents a low cost and very low-profile, since the whole antenna thickness is of $\lambda_0/15$ at the center frequency. Moreover, the proposed antenna has advantages in terms of light weight, low-profile, and compact size. All dielectric substrates of the proposed structure are inexpensive FR-4 printed circuit board. This offers a cost-effective solution for many wireless communication systems.

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Fig. 6. Measured radiation patterns for the microstrip-fed slot antenna with the metasurface in $E$-plane. (a) 2300 MHz, (b) 2450 MHz and (c) 2500 MHz.

Fig. 7. Measured radiation patterns for the microstrip-fed slot antenna with the metasurface in $H$-plane. (a) 2300 MHz, (b) 2450 MHz and (c) 2500 MHz.

Fig. 8. Simulated and measured realized gains of the microstrip-fed slot antenna with and without the metasurface.

Fig. 9. Distributions of the microstrip-fed slot antenna at 2.45 GHz (a) with the metasurface and (b) without the metasurface.

REFERENCES


