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밀리미터파 안테나 모듈 기성품의 고착화된 기능을 향상시키는 메타 재질 표면

A Metasurface Improving the Fixed Function of a Ready-Made mm-Wave Antenna Module

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[요 약]

본 논문에서는 기존의 밀리미터파 안테나 시스템의 기능을 개선하기 위한 새로운 접근법을 제시한다. 장치의 주어진 기하학적 구조 및 고정된 전기적 특성에 적합한 메타물질 표면을 설계함으로써, RF 제품의 방사 필드들의 지향성 및 더 높은 이득을 갖도록 한다. 단일 패치에 대해 주기적 메타물질을 사용하는 다른 설계와 달리, 비주기적 메타표면은 2개의 패치를 처리할 수 있다. 24GHz-라디오 링크에서 더 높은 수신 신호 강도 및 더 긴 RF 경로에 대해, 비주기적 메타표면은 방사 필드들을 10 dB 향상시킨다.

[Abstract]

In this article, a new approach is presented to improve the unchangeable function of a ready-made millimeter-wave antenna system. By designing a metamaterial surface appropriate for the given geometry and fixed electrical characteristics of the device, the properties of the radiated fields of the RF product are changed to have directivity and higher antenna gain. Unlike other designs using periodic metamaterials for a single patch, an aperiodic metasurface is developed to handle two patches. For a higher received signal strength and a longer RF path in the 24 GHz-radio link, an aperiodic metasurface enhances the radiated fields by 10 dB.

Key word : Millimeter-wave device, Antenna, Metamaterial surface, Antenna gain.

색인어 : 밀리미터파 장치, 안테나, 메타물질표면, 안테나 이득.

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Ⅰ. Introduction

Wireless links are built everywhere for social activities and corporate businesses going on these days. Cultural gatherings are telecast from stadiums to viewers at home, and business deals are reported from a foreign country to the headquarters by way of the wireless links [1]. They are constructed as WiFi, LTE-A services and so on. The radio links they have provided have enabled one to call and talk to someone at the other end of the line. The subscribers to the radio link services need to tolerate limits in amount and speed of data they get. This is related to the frequency bands and hardware the so-called legacy mobile communication services.

To push the bar from the limited amount and speed of mobile data, broadband communication has been suggested and developed as millimeter-wave technologies [2]-[4]. The channels of millimeter-wave bands are so wide that high data transmission rates can be realized. Like UHF bands, a millimeter-wave communication system is made up of up down converters and an antenna. Because the frequency is very high and quality of communication is sensitive to attenuation factors of materials used for the wireless circuits, more care should be given to designs of millimeter-wave components. When they cannot overcome degradation due to the attenuation, high data transmission is not attainable.

As one of the components, the antenna is prone to degradation, for it is a resonating structure and made with the substrate lossy at the high frequency. To overturn the challenge, various techniques were introduced to the designs of millimeter-wave antennas as follows. Y. Lee et al. presented an array antenna on an SoC [5]. The radiators are fed by the pins of a chip. Y. Kim et al. obtained the data transmission-rate above 1 Gbps by using a transmitting antenna and an array in the receiver [6]. J. Park et al. experienced the communication link screwed up by an RF noise. W. Roh et al. emphasized the adoption of beamforming antennas can make the wireless system versatile [7]. Y.-J. Cheng showed SIW components combined with planar antennas [8]. P. Arcioni et al. reported that a planar laminated antenna works for the millimeter-wave [9]. As others, D. Liu adapted one block to another block by minimizing the return loss [10]. F. He et al. suggested the combination of the planar circuits with planar antennas [11]. A volumetric antenna uses its slots coupled to the radiators [12].

N. Ojaroudiparchin et al. put 1-by-8 array antennas together with a dipole [13]. J. Cho et al designed two 2D beamforming networks each of which radiates electromagnetic fields at four angles at a millimeter-wave frequency [14],[15]. The surveyed antennas are representatives of non-metamaterials.

This article proposes a small-sized millimeter-wave antenna which gets improvement in beam directivity and antenna gain. Besides, implementation will cost much less than other high- frequency antennas. Given an off-the-shelf type of source of radiation with a fixed electromagnetic function, a metamaterial surface is devised to increase the antenna gain by converting the diverging wave of the primary source to a directive wave. The design method differs from others now that the metamaterial has a non-periodic metal pattern and takes care of the incident waves from two patch antennas as the primary source, while others adopt periodic metal pattern and handles a single patch. The patches are realized by mimicking the structure of a commercial antenna module and the metamaterial surface is fabricated as the metal pattern on FR-4 substrate and added to the patches. This approach results in enhanced antenna gain of 10 dB meaning the stronger received signal due to heightened directivity. The experiment backs up the simulation for the proposed design scheme

Ⅱ. Realization of the millimeter-wave antenna and the millimeter-wave metamaterial structure

Before starting the design of the antenna system, the following figure depicts positive effects the use of the metasurface provides for an ordinary antenna.

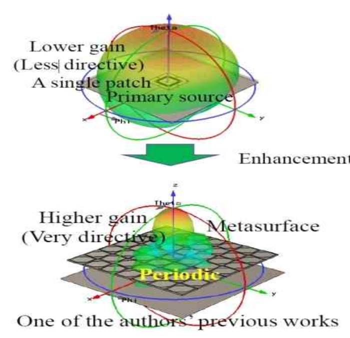
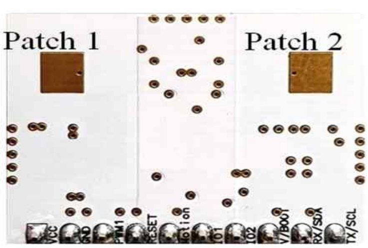
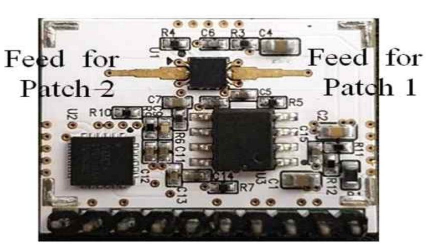


Fig. 1. Enancement in the radiated field performance of the ordinary patch antenna by using the metasurface.

Placing the metamaterial surface over the patch antenna changes a wide beam-pattern of the primary source to a narrow beam pattern giving advantage in directivity and gain as in Fig. 1. It is noted from the previous work that the metasurface has a periodic pattern and treats the impinging wave from a single patch. In most cases of configuring communication networking services, commercial modules are employed and they are assembled with other parts in a PCB. The following figure shows a typical form of the off-the-shelf wireless module. As for the communication system development the entire architecture is divided into parts and blocks, which come form different makers. Fig. 2 is the integrated shape of the digital block combined with the up down converter and RF block. The antenna part from the RF block comprises patch 1 and patch 2 connected to the feeds led to the pins of the chips. Once the system developent is finished, the RF Functions are unchangeable. As above, using only the two patches gives a lower antenna gain such as 0.41dBi at 24GHz, which limits the distance of signal transmission like the near zone in wireless networking. Additionally, the two patches have a wide spacing which is almost impossible to have constructive interference, in other words, low in gain. The only way to change the fixed functions is to introduce an external device. It is the metasurface. The design of the proper metasurface necessitates the primary source. So, the two patches and feeds as in the figure above are mimicked first in the electromagnetic CAD program. And then, they are adopted as the source of field radiation for the metasurface.



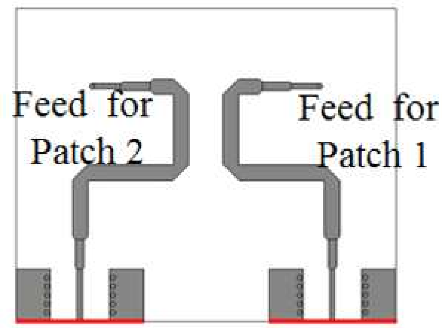
Front-side of a commercial wireless module



Back-side of a commercial wireless module

Fig. 2. Ready-made comunication module.

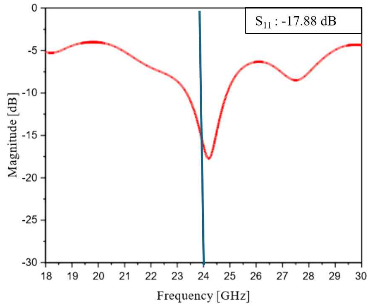
(a)



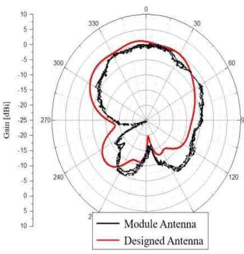
(b)

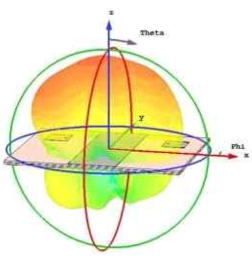
Fig. 3 Antenna block from Fig. 2 translated into the EM simulation (a) patches, and (b) feeds.

Each of the rectangular patches in Fig. 3 is a metallized area of 3.0 2.5 mm^2 on the 0.8-mm thick FR-4 substrate. Fig.3 (a) and Fig. 3(b) show patches and feeds. Patch 2 is distant from patch 1 by 12.8 mm across the vertical metal strip, which makes the design of metasurfaces more difficult than the conventional techniques. The patches on the front side of the wireless module are connected to the feeds at the back. In the usual cases, the structure of the feed for the patch is very simple such as one straight transmission line. However, as far as the feeding structure of the commercial RF module should be copied to observe a positive change from the ready-made product, it is crooked and bent as the cascade of inhomogeneous segments of transmission line. In addition, at the bottom edge of the backside, two CPW parts are assumed as the input ports of the feeds. No matter how complicated they look, the impedance matching with a low S_{11}-value must be obtained at the target frequency

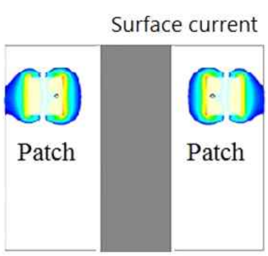


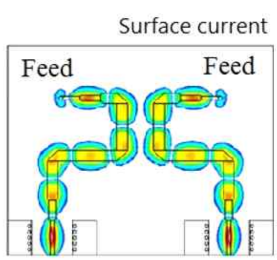
(a)





(b) (c)

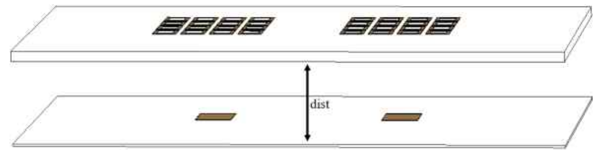




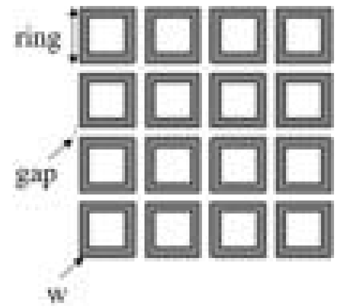
(d) (e)

Fig. 4 (a) Impedance matching , (b) Beam-pattern of the patch with the complicated feeding structure , (c) 3D plot of the beam-pattern , (d) surface current density on the front , (e) Surface current on the backside.

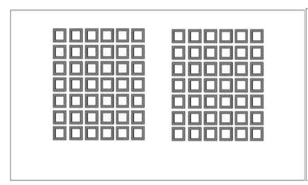
The impedance at the input port is matched at 24 GHz as shown in S11 view-graph of Fig. 4(a). That satisfies the resonance condition where the S11-value becomes very low. It is much less than -10 dB. The radiated field is generated at the resonance frequency and it is plotted as Fig.'s 4(b) and 4(c). The far-fields patterns of the purchased wireless module and the CAD model have good agreement except that they have difference at some angles in the back radiation area. It is inferred that the backside of the real module is crowded with metal covered spots and routes causing radiation leakage. The resonance is seen on the left and the smooth flow due to the impedance matching on the right as in Fig. 4(d).

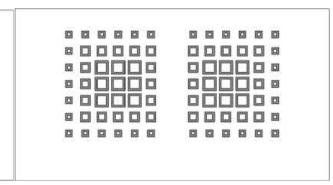


(a)



(b)



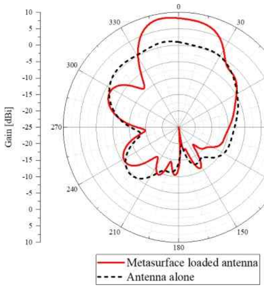


(c) (d)

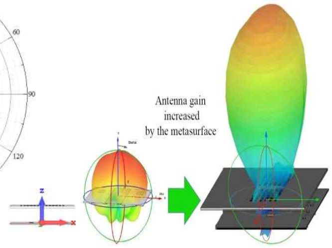
Fig. 5. Metamaterial surface put over the two patches as the source of radiation (a) structure, (b) geometric parameters of the metal pattern, (c) Initially, periodic pattern metasurface (d) aperiodic pattern.

The 3D view of the structure is presented in Fig. 5(a). Inspired by placing antenna elements periodically, the geometrical parameters ring, ring width and gap between the rings are set to 1.9 mm, 0.1 mm and 0.4 mm, respectively. dist. is 6.6 mm for Fig.'s 5(a) and (b). The metal pattern is initially periodic in Fig. 5(c) and has two groups interfering with each other and with the metal strip below. As the two kinds of interference to be decreased, in order to overcome the shortcomings resulting from asymmetric environment around edges of the patches, the metal pattern finally becomes aperiodic and non-uniform as in Fig. 5(d).

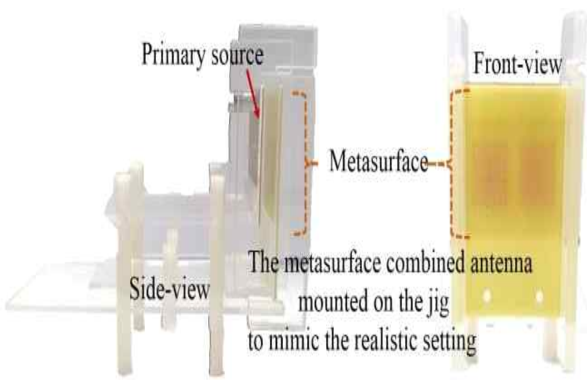
Merits of the proposed design are investigated by the electromagnetic simulation, experimental tests and comparison of results. The metasurface of Fig. 5(d) is applied to the patches, and the simulated 2D and 3D beam-patterns show the merits as in Fig.'s 6(a) and (b). The antenna gain is enhanced by 10 dB. The flux of the fields from the primary source turns denser, and the beam gets directive and pushes the antenna gain up despite the use of a relatively lossy substrate to cut down



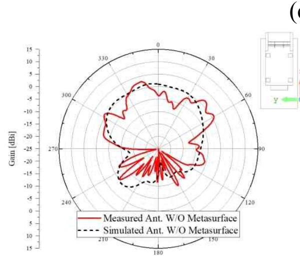
(a)



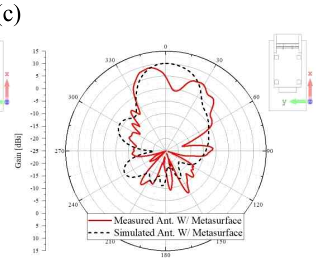
(b)



(c)



(d)



(e)

Fig. 6. Observation of positive effects of using metasurface (a) Increased gain checked from the 2D simulated field-patterns (b)Increased gain checked from the 3D simulated field-patterns (c) Manufactured structre (d) Comparing the simulated and measured field-patterns of the radiation source (e) Comparing the simluated and measured field-patterns of the metasurface-combined antenna.

Table 1. Comparison between the proposed metasurface and without metasurface .

Antenna / Gain (Max)	Ant. W/O Metasurface	Ant. W/ Metasurface
Simulation	0.18 dBi	9.82 dBi
Measurment	0.27 dBi	8.35 dBi

on the cost. The final structure is fabricated through PCB etching, realizing the mounting jig and plugging the cable adaptor as in Fig. 6(c). The simulated and measured far-field patterns for the source of radiation are compared as in Fig. 6(d). They commonly have very low gains and wide beamwidths. On the contrary, the beam-patterns both in simulation and experiment com to have increased gains as in Fig. 6(e). The discrepancy between the simulated and measured far-field patterns stem mainly from mechanical errors occurring in assembling such as misalignment between planes, asynchronous orientations of the parallel planes in the jig, blobs on the cut's observable by the camera in Appendix, uneven conductivity on soldered spots observable by RM2610 in Appendix, etc. It should not be forgotten that the performance of millimeter-waves is sensitive to even a small change in geometry and materials.

Ⅲ. Conclusion

This article suggests a novel metamaterial surface to change the fixed RF function of an off-the-rack millimeter-wave communication module. In detail, the wide-beam pattern and low antenna gain of the commercial module are changed to be a directive far-field pattern and high gain. Imitating the layout and configuration of the commercial device, the geometry of the primary source is drawn in the CAD and its characteristics are investigated to obtain the information for the design of the metasurface. Considering the two patches and feeds laid in a different manner from the ordinary practices, a periodic and non-uniform metal pattern metasurface is figured out by modifying the periodic metal rings on the substrate. From the simulated and measured beam-properties, the antenna comes to have a directive beam and a high gain as the 10-dB improvement. This new metasurface, overcoming the attenuation of the cheap substrate and mechanical errors in making the 3D geometry, is used to increase the strength of radiated fields at the millimeter-wave. Also, it reduces the cost of fabrication unlike the conventional array antennas that are expensive and undergo the dielectric material loss.

Acknowledgments

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References

[1] H. Kwon, K. Kim, and C. Lee, “The unified UE baseband modem hardware platform architecture for 3GPP specification”, *The Journal of Communications and Networks,* Vol. 13, No. 1, pp.70-76, February. 2011.

[2] T. Roos, P. Myllymaki, and H. Tirri, “A statistical modeling approach to location estimation”, *IEEE Transactions on Mobile Computing*, Vol. 1, No. 1, pp. 59-69, January 2002 .

[3] H. Liu and G. Li, *OFDM-Based Broadband Wireless Networks: Design and Optimization*, Hoboken, NJ: Wiley-Interscience, November. 2005.

[4] T. L. Marzetta, “How much training is required for multiuser MIMO.” in *2006 Fortieth Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, pp. 359– 363, November. 2006.

[5] W. Hong, K. Baek and Y. Lee, “Study and prototyping of practically large- scale mm-wave antenna systems for 5G cellular devices,” *IEEE Communication Magazine*, Vol. 52, pp. 63–69, 2014.

[6] Y. Kim and W. Roh, “Feasibility of mobile cellular communications at millimeter wave frequency,” *IEEE Journal of Selected Topics in Signal Processing*, Vol. 10, No. 3, pp. 589–599, April. 2016.

[7] W. Roh, J.-Y. Seol and J. Park, “Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results,” *IEEE Communication Magazine*., Vol. 52, pp. 106–113, February. 2014.

[8] Y.-J. Cheng, *Substrate Integrated Antennas and Arrays*, CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2016.

[9] Y. Cassivi, L. Perregrini and P. Arcioni, “Dispersion characteristics of substrate integrated rectangular waveguide,” *IEEE Microwave and Wireless Components Letters*. Vol. 12, No. 9 , pp. 333–335, September. 2002.

[10] D. Liu, *Advanced Millimeter-Wave Technologies: Antennas, Packaging and Circuits*, Wiley: New York, NY, USA, 2009.

[11] F. He, K. Wu and W. Hong, “Low-cost 60 GHz smart antenna receiver subsystem based on substrate integrated waveguide technology,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 60 , No. 4, pp. 1156–1165, April 2012.

[12] S. Yamamoto, J. Hirokawa and M. Ando, “A beam switching slot array with a 4-way Butler matrix installed in a single layer post-wall waveguide,” *IEICE Transactions on Communication*, Vol. 86, pp. 1653–1659, February 2002.

[13] N. Ojaroudiparchin, M. Shen and G. F. Pedersen, “Multi-layer 5G mobile phone antenna for multi-user MIMO communications,” in *Proceedings of the 2015 23rd Telecommunications Forum*, Telfor, Belgrade: Serbia, pp. 24–26, November. 2015.

[14] M. Jeon, Y. Seo, J. Cho, C. Lee, J. Jang, Y. Lee, H.-W. Kwon and S. Kahng, “Investigation on beam alignment of a microstrip-line Butler matrix and an SIW Butler matrix for 5G beamforming antennas through RF-to-RF wireless sensing and 64-QAM tests,” *Sensors* 2021, 21, 6830.

[15] I. Moon, W. Kim, Y. Seo, and S. Kahng, “A metamaterial Surface avoiding loss from the Radome for a millimeter-wave signal-sensing array antenna,” *Sensors*, Vol. 24, No. 3, Online publication, Article ID: 1018, Feb. 2024.

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