Metamaterial Lensing Surface for a Weight-Reduced Metal Waveguide Antenna on Satellites

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***Abstract*—In this paper, a new method is suggested to relieve satellite payloads of rapid growth in weight attributed to metal waveguide antennas. A metasurface lens does away with the waveguide array antenna as a heavy structure but employs a short waveguide which is combined with the metasurface. Antenna directivity and gain become high though the system gets lighter than the conventional development methods. A metasurface lens is designed to increase the antenna gain of an X-band metal waveguide antenna and is observed to jump by over 7 dB. The far-field patterns of the primary antenna and the final structure are given to show benefits of this method and the compact size will be mentioned**

Keywords—Antenna, Metasurface, High directivity, Low weight

I. Introduction

The altitudes of artificial satellites have been diversified more than ever before. Coverages and operations of global telecommunication services determine where they are located and flying. As the terrestrial networks are expected to reach for something off the ground to link the caller at one spot with his or her counterpart at a far-away spot, a new paradigm so called NTN brings the locations of newly produced satellites down from 36,000km to 550km or above[1,2]. It is LEO satellites that draw attention and investment for faster and wider wireless links by being connected to 5G and 6G. Unlike GEO satellites, a ton of LEO satellites are being deployed to form a vast network named constellation. Each of them must be lighter and agile.

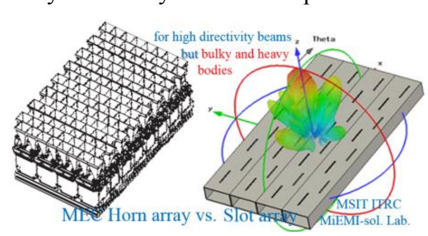
A satellite is made up of mechanical parts and electric parts. Most of the mechanical parts are indispensable to housing and moving, which makes it hard to take many elements away. Electrical parts are also so crucial that they cannot remove many. It seems too tough to come up with what should be gone away to make a satellite low in weight. However, an idea hits us that attention ought to be paid to waveguide structures in the RF block essential to communication. Seeing satellite transponders, there are the waveguide feed-assembly and waveguide antenna. Leaving the feed assembly alone, the waveguide antenna is under a microscope, because a waveguide is a relatively heavy apparatus. It makes things worse when an array of waveguide radiating elements is adopted. A question arises whether there is a way to make the waveguide antenna smaller without loss of functional achievement. It is hinted by the use of metamaterials[3].

Since the advent of metamaterials, much literature has reported positive effects. Among them, performance enhancement by a reduced-sized structure is attractive. Instead of an array antenna, a few radiating elements are taken and placed under a lens that is neither convex nor concave, but bends the incoming wave to a specified angle[4-6]. Naobumi, Gaufillet and Zhang showed lenses changing the ideal rays from the source of radiation to the plane-wave. Different from them, the wave is guided rather than being radiated and travels through curved lenses such as Luneburg ones resulting in the concentration to one direction[7-11]. These are a sort of longitudinally distributed lens together with the end-fire antenna coupled to the lens[12]. These are long geometries. To prevent the antenna system from being long, transversely distributed lenses have been introduced in a plenty of articles such as [12-14]. In most of the cases, patches or horn antennas are adopted as the sources of radiation. The broad beam from a patch as the primary source is changed to a narrow beam as G. B. Reddy and C. Kohlberger et al introduced. On the contrary, an open end of a long waveguide is working as the source of radiation for the flat lens[12-14]. The broad far-field from the end of the waveguide becomes a narrow far-field pattern.

In this paper, a new approach is conducted to enhance the gain of the radiated field and keep the device from becoming big. Conversely to [7-17] or others who use patches or horns, a short waveguide with one slit or two is employed as the primary source and its lower gain beam is converted to a higher gain beam after passing a transverse metasurface lens. At an X-band which ends up very large as an array antenna or huge with horns by the conventional techniques, this proposed method turns out to be improvement in the antenna gain and a small structure which makes the system lighter.

II. A New Antenna for Reduced Size and Weight

A satellite tends to be overweight when it should have a waveguide array antenna system with its power divider.

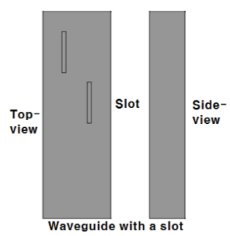


(a)

(b)

Fig. 1. Waveguide array antennas (a)Radiators (b)Power-divider

Satellite payload developers take it for granted that a horn array or a slot array waveguide antenna as in Fig. 1(a) is a must-use gadget to generate a high directivity beam which is appropriate for covering customized service-areas and making up for the path loss of the radio wave on the path between the ground and the high altitude. Fig. 1(b) is the waveguide power divider as part of the feed assembly for either of the two kinds of arrays in Fig. 1(a). Radiating elements and the feeds account for the weight of the satellite. Taking into account the material and manufacturing method of producing waveguide radiators and components which are well known as ingot aluminum and milling machining, the combination of Fig. 1(a) and Fig. 1(b) ends up with a heavy piece of equipment. This will frustrate the SatCom payload developers in adopting the conventional high-gain antenna to the communication system despite their electrical characteristics. It becomes a big concern when a lot of small satellites are demanded to be carried at a pod in a rocket, ejected to numerous positions on an orbit and move swiftly. This is why a novel approach is needed to build small satellites.



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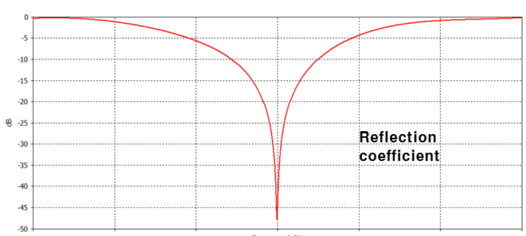

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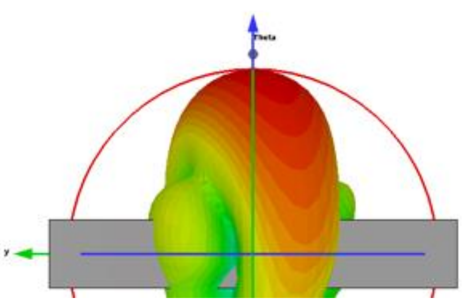
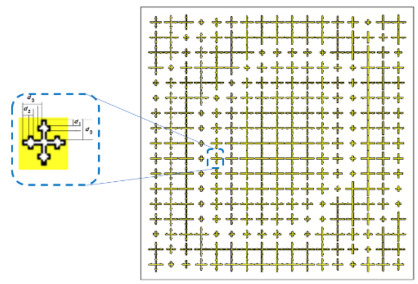


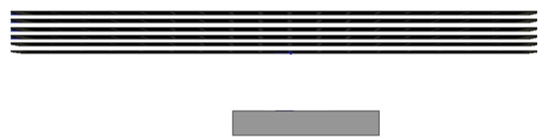
(c)

Fig. 2. A small slot array waveguide antenna (a)Top- and side-views of the structure (b)S_{11} of (a) (c)Beam-pattern of (a) at the resonance frequency by the structure

The slots are measured 2 mmX19.7mm on a 32.6 mmX100 mmX16.3 mm sized waveguide shown in Fig. 2(a). These geometrical parameters let this short waveguide antenna resonate at the center frequency of an X-band satellite communication as seen in Fig 2(b). The far-field by this antenna is given as Fig. 2(c) where the antenna gain is 9 dBi as a torsional fan-beam. In the longitudinal axis of the antenna, the beam is very wide and insufficient. competent unsuitable. As the use of an array antenna of an extended size is avoided due to the reason, a method beating the odds is proposed. For this purpose, a metamaterial lens is designed and combined with the small waveguide antenna.



(a)



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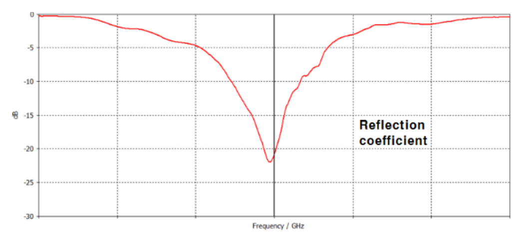

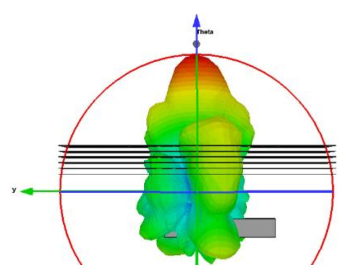

(d)

Fig. 3. A metasurface lens helping the antenna with the main functins (a)Metasurface lens and the unit cell (b)Side-view of the metasurface combined with the short waveguide (c)S_{11} of (b) (d)Beam-pattern of (b)

The far-field from the short waveguide has a low antenna gain and should pass through the metasurface lens in Fig. 3(a). It provides a phase distribution for the incident wave from the primary source to experience the phase shift from point to point as the cells. The unit cell is realized with a metal cruciform on a dielectric plane and its size and variation result in the desired phase shift for the far-field from the short waveguide, which is described in Fig. 3(b). At the input port of the waveguide antenna, the reflection coefficient has the same resonance frequency even after putting the primary source together with the metasurface. The gap is less than 5 cm shorter than the total height of the conventional waveguide array antenna for the X-band. The far-field comes to have a high gain increased by over 7 dB and the torsional beam has got back to vertical-axis symmetry. It is meaningful to get this effect with a transverse structure not with an end-fire one. Additionally, antenna directivity has been improved without resorting to a large array antenna. Compared to the array equal to the one with 16X16 elements or more, the total area is around one forth or smaller, which implies this is much lighter even before mentioning the waveguide power divider. Cost for maintenance as well as manufacturing will be lower. The suggested method is a good candidate for LEO satellites being fabricated en masse.

III. Conclusion

This paper shows a special method that the far-field of a short waveguide antenna is transformed to a highly directive beam-pattern by the use of a new metamaterial lens. Without the large array antenna and its heavy power divider, the short waveguide as the source of radiation can raise the antenna gain as much as in case where a two-stage power amplifier might be adopted. It is worth assessing that the antenna performance is enhanced as a small volume of structure. This boils down to reduction in weight of the antenna system, signifying this scheme proper for giving a solution to LEO satellites.

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