Dual band focusing system based on metasurfaces

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Introduction

In the satellite communication links can be found several system like Globalstar, Teledesic, Iridium or more future one Iridium Next. Those systems are mostly used in the high speed telecommunication and differ in the topology and operating frequency bands. The one concepts is based on a simple satellite system with separated uplink and downlink operating at S-band (Globstar) and the other has complex space segment with one carrier served for uplink and downlink operating at Ka-band (Iridium). To avoid of electromagnetic pollution in environments of different satellite systems, a high focusing for each system is demanded. Moreover, the modern satellites offering broad band communication link for data transfer and telecommunication and requires low-cost focusing system. Instead of wide band antennas working simultaneously at uplink and downlink ranges, more practical can be application of dual band focusing system. In such system each channel is covered with separate antenna or with one antenna providing double operating frequencies bands.

A conventional dual band system is based on stacked ring antennas or multi-band microstrip patch antenna. In the classical stacked system the only one ring is excited directly from the probe where the other one is coupled through the fringing fields. The two rings are coupled cavities supporting different fringing fields and consequently providing two resonant frequencies, i.e. two operating bands. Unfortunately such system offers low directivity and in consequence the better solution for dual focusing system is required.

The new concept of dual band focusing system is based on transition between surface wave (SW) and leaky wave (LW) obtained by modulation of surface impedance. The antenna performance is done by interaction between cylindrical surface waves excited by omnidirectional probe and an inhomogeneous surface impedance with an asymmetric circular pattern. In such antenna, the surface impedance interaction transforms a bounded TM_0 surface wave into linear polarized leaky wave with conical radiation for downlink and uplink bands. The asymmetry of the pattern can be presented by different radius of opposite half rings or sections where each represents modulation for a given frequency. The modulation of the surface impedance is provided by a grounded dielectric slab with an asymmetric-sinusoidal thickness or a texture of dense printed patches with sizes variable with asymmetric-sinusoidal function. The phenomenology of the local interaction between an angular portion of cylindrical surface wave wavefront and an angular sector of the spiral is described by means of a 2D problem of a sinusoidal reactance excited by the wave. The local surface impedance is defined in term of holographic principle to support leaky wave radiation. The impedance can be expressed by variable reactance depending on thickness of a ground dielectric slab. As well, the surface impedance can be synthesized by printing a dense texture of square metal patches (or different shape) on a grounded slab with constant period and variable sizes, like in holographic antenna. With an assumption of slowly varying of dimension of unit cell with keeping constant period, the characterization of surface impedance can be achieved like as uniform periodic structure. Keeping in mind size of the unit cell and period much lower then wavelength (operating in long wave regime) the lower impedance levels are represented by smaller patches and the higher impedance levels by larger patches.

In presented work is shown a concept of dual antenna which is able to create conical beam at two frequency ranges. For this antenna is proposed particular excitation to lunch surface wave which has to make transition with leaky wave by modulation of the surface impedance. Basing on the concept of metasurface created for the dual band antenna was proposed flat holographic antenna which is able scan all space by pencil beam. For this system is also proposed excitation which allows to create surface wave only under particular modulated surface to create given direction of radiation. The two concepts are presented and validated with electromagnetic simulations.

Uniform metasurface modulation

The metasurface is a surface made of printed patches over the grounded dielectric substrate. The patches are periodically distributed and their sizes are match smaller then surface wavelength. In this concept the metasurface can be treated as a continues medium with a uniform inductive reactance. For which can be directly applied boundary conditions at tangential components of electric and magnetic fields at $z=0$.

$$jX_s z\times(H\times z)=E\times z \tag{1}$$

, where X_s is reactance defined by positive scalar. With this assumption it can be supposed that metasurface supports cylindrical TM_0 of surface wave and the tangent fields are written in cylindrical coordinators as

$$\begin{aligned} E_{sw}^{\tan} &= J_{sw} jX_s H_1^{(2)}(\beta_{sw}\rho)\hat{\rho} \\ H_{sw}^{\tan} &= -J_{sw} H_1^{(2)}(\beta_{sw}\rho)\hat{\varphi} \end{aligned} \tag{2}$$

, where $H^{(2)}_1$ is a first order of second kind of Hankel function. The wavenumber of surface wave β_{sw} can be found from transverse resonance between metasurface and free space impedance, and defined with

$$\beta_{sw} = k_0\sqrt{1 + X_s / \zeta_0} \tag{3}$$

, where k_0 and ζ_0 are respectively free space wavenumber and impedance. The radiation from the metasurface occurs when $\beta_{sw} > k_0$ and the reactance is positive. The complex amplitude J_{sw} of the surface wave depends on a type of excitation.

The surface wave wavenumber is defined with reactance of the metasurface. The variation of the reactance can obtained with periodic radial modulation, keeping the size of period p in long wave regime, and it is expressed by sinusoidal function

$$X_s(\rho) = X_s[1 + M\sin(K\rho)] \tag{4}$$

, where X_{as} is average reactance value, M is a modulation index and $K = 2\pi/p$. With such modulation of the reactance the surface wave can be transformed to leaky wave which creates conical beam. The modulation of the impedance depends only on ρ and to cover all surface it is need only rotate the function along z, Fig. 1.

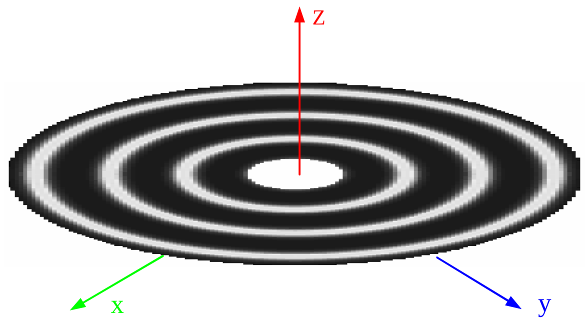

Fig. 1 Modlation of surface impedance for conical beam radiation pattern.

The real and imagine part of modulated reactance with a sinusoidal function is perturbed, however they are very small comparing to the wavenumber of surface wave.

The fields in (2) for radial periodic modulation can be defined with Floquet modes of wavenumber $k_{\rho n} = \beta_{sw} + n2\pi/p$. Only Floquet modes with phase velocity smaller then speed of light can create leaky wave and radiation beam, i.e. those satisfying condition of $|\mathrm{Re}(k_{\rho n})| < k_0$

$$|\beta_{sw} + nK| < k_0 \tag{5}$$

The LW dominate and radiating mode is n = -1 what allows to specify direction of beam point θ_0, and the **(5)** can be rewritten as

$$\beta_{sw} - K < k_0 \sin\theta_0 \tag{6}$$

This leads to determinate two possible direction of LW forward and backward, as well related radiation beam. The conditions form normalize reactance for forward radiation direction $\theta_0 > 0$ i.e. $K > \beta_{sw}$ is

$$X_s / \zeta_0 \approx \sqrt{(\lambda_0 / p - \sin|\theta_0|)^2 - 1} \tag{7}$$

, where λ_0 is free space wavelength. The condition for backward radiation, defined as $\theta_0 < 0$ i.e. $K < \beta_{sw}$, is

$$X_s / \zeta_0 \approx \sqrt{(\lambda_0 / p + \sin|\theta_0|)^2 - 1} \quad (8)$$

With forward and backward radiation can be obtained the same conical beam, however the forward one requires higher values or reactance what lead to larger and sensitive design of metasurface.

Dual band metasurface modulation

The modulation of surface impedance can be obtained with variation of thickness of the grounded substrate, i.e. corrugated dielectric antenna. More practical modulation of reactance can be done with metasurface generated with printed texture of patches on grounded substrate, i.e. holographic antenna. The patches can be of any shape (in design is used square shape) but they are limited with size and period which has to fit the long wave regime conditions. The grating of metasurface is dense with smooth variation of impedance, thus it can be assumed that each pixel of metasurface is defined by uniform periodic structure. The characterization of impedance for such medium can be obtained with pole-zero method, or other.

The dual band focusing system is based on application two metasurface modulations defined for a given frequency at one layer. The layer is divided symmetrically on eight parts, four are dedicated for one frequency band and other four for the second frequency band, Fig. 2.

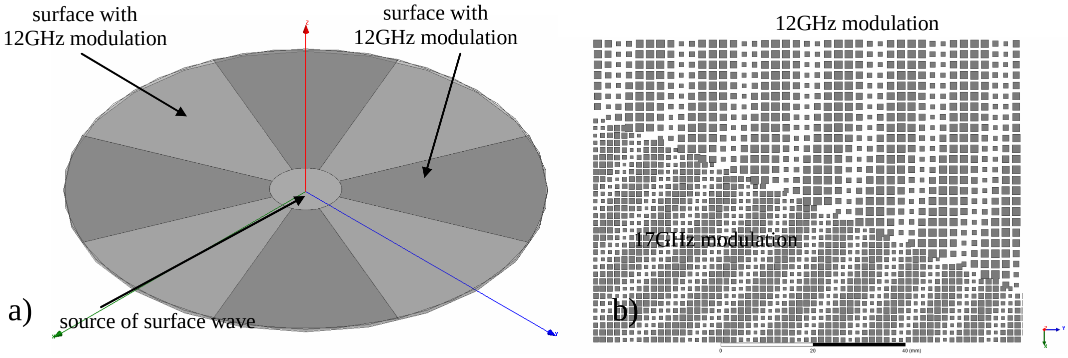

Fig. 2 a) Division of the surface of antenna for application of two metasurface modulations defined for different frequencies. b) Example of used metasurface modulation in the design of antenna working at 12GHz and 17GHz.

At each frequencies only defined part of the surface should radiated, thus it is required to lunch surface wave in proper way. It is done with application four pin source covered by a metallic disk. The opposite feeds are in a distance of half of surface wave length for a given frequency and they are in phase as well each is 180deg different to the next feed. This constellation allows to lunch surface waves with four maximums of the fields and excited only given part of the surface of the antenna, Fig. 3. To excited the other part of surface designed for the second frequency is used the same approach only rotated to feed given surface modulation.

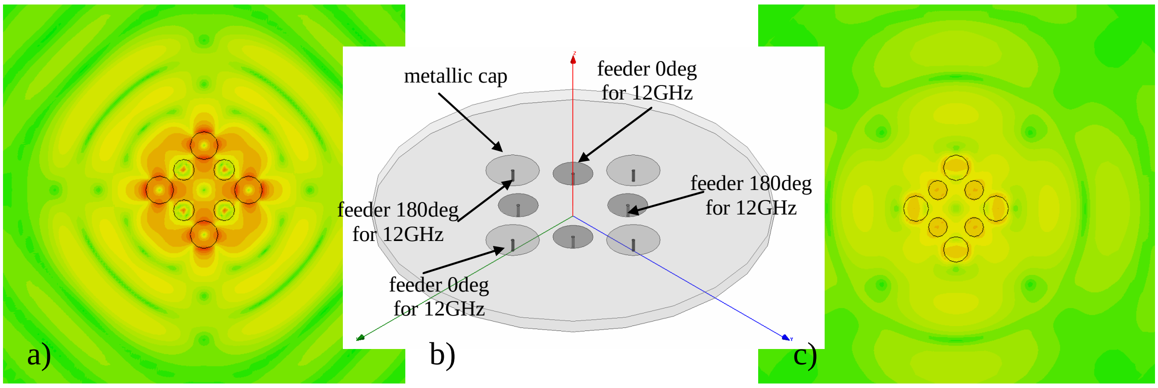

Fig. 3 Fields distribution over the surface of grounded dielectric substrate at a) 12GHz and c) 17GHz. b) Excitation configuration to lunch surface wave in four directions for two different frequencies.

The plots of magnetic field distribution over a grounded slab are obtained with electromagnetic simulator HFSS. The surface wave is lunched with four beams of 60deg lobes, where the corner of metasurface covers 45deg. The leaking of energy to the part of metasurface designed for other frequency dose not contribute much with the global results of radiation pattern, i.e. only the correct part provides transition between surface wave to leaky wave at given frequency.

The metasurface for dual antenna is designed to operate at backward mode radiation, with a pointing beam at θ_0 = -45deg, and it operates at 12GHz and 17GHz frequency ranges. The grating of the patches for two operating frequencies are presented on Fig. 3b. The verification of the antenna is done with Ansoft Designer. The directivity patterns are presented for two operating frequency bands with consideration of mishmash of the metasurface and sweep of frequency . The maximum directivity at -45deg is obtained at 12.2GHz of first frequency range and at 17.2GHz for the second frequency range, Fig. 4.

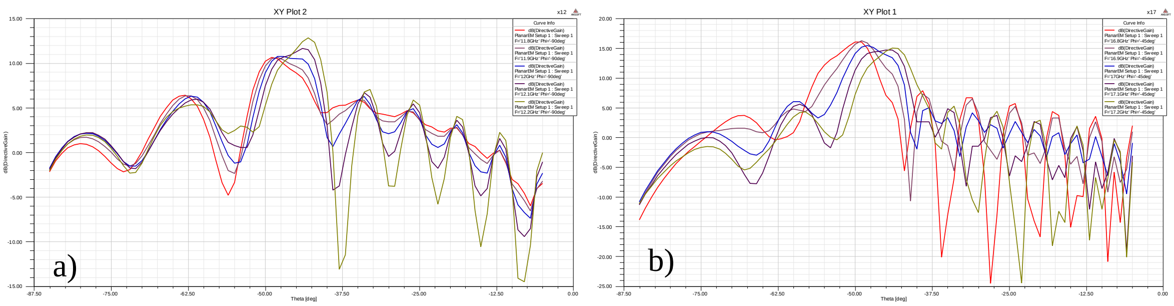

Fig. 4 Directivity patterns of antenna contained only four parts of metasurface dedicated to a) 12GHz and b) 17GHz.

The proposed antenna radiates in four directions at each frequency, to cover all conical beam it is required to use mechanical rotation or application of more sections dividing surface of antenna to achieve more uniform pattern.

Varying of direction of beam radiation with metasurface modulation

The metasurface of antenna can be design in such manner that with varying of azimuthally direction of wavefront of SW the direction of pencil beam radiation will be changed. This allows to obtain flat holographic antenna with mechanical scanning of radiation direction. The metasurface of such antenna is design in the same way like for dual band antenna, however it includes dependence of reactance modulation of azimuthal angle to provide radiation direction given as

$$\vec{r} = \sin\theta\cos\varphi\hat{x} + \sin\theta\sin\varphi\hat{y} + \cos\theta\hat{z} \qquad (9)$$

The smooth variation of periodicity of modulation along radial component is obtained with a discontinuity at the point where modulation starts and ends, Fig. 5.

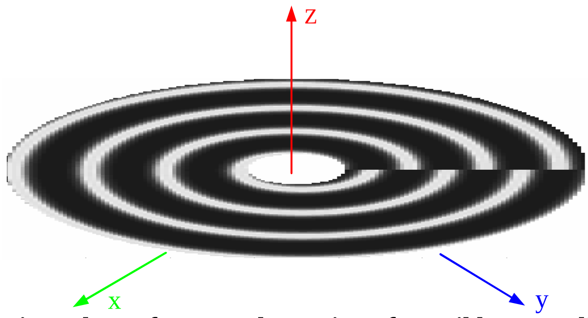

Fig. 5 Modulation of surface impedance for smooth varying of pencil beam radiation.

Main lobe is pointing at a given angle only when surface wave is lunched on a portion of the modulated surface. To satisfy this requirement, the ground plane exists only under a part of metasurface which will be excited. The azimuthal variation of the lunching of surface wave is obtained by mechanical rotation of ground plane and a feeder. For low dissipation of energy in the design it is needed to consider directive feeder. It can be constructed with four pin covered with a metallic disc, which are in the distance from each other of quarter of surface wave length. The two excitations parallel to the normal of surface wave are in phase as well they are in 90deg difference to the other two excitations, Fig. 6a. Other possibility of launching directional surface wave is application of reflector effect. It is done with, a pin covered with a metallic disc where one half of the end of cover is shorted to the ground plane, Fig. 6b. The radius of the metallic disk should be around quarter of wavelength of guided wave in the substrate.

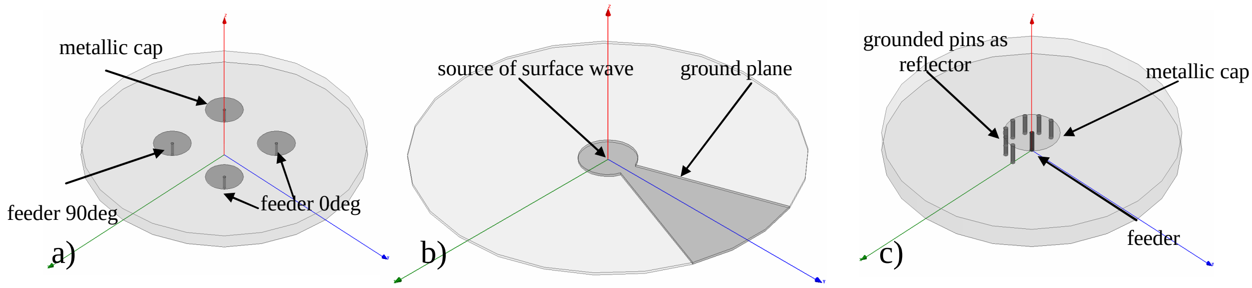

Fig. 6 Excitations of the surface wave obtained with a) four pins covered by a metallic disks and c) one pin with a shorts between metallic disk and ground plane. b) Setup of antenna to excited surface wave in a given direction.

In the verification of the concept was used excitation as presented on Fig. 6a, designed for lunching surface wave at 17GHz. The directivity pattern was obtained with HFSS (it is required to use finite ground plane). The metasurface is done with the same parameters like for dual antenna operating at 17GHz, Fig. 3b.

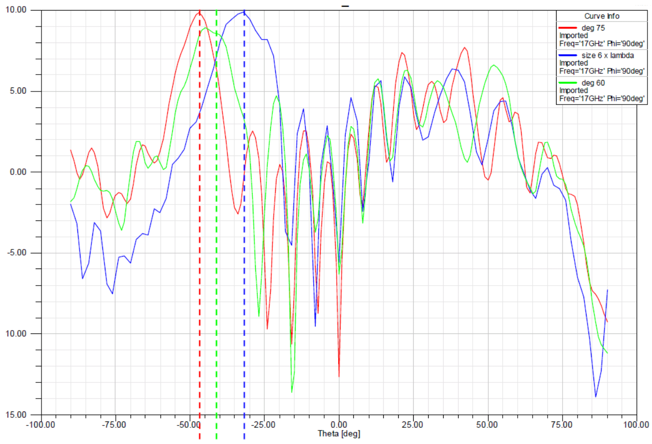

Fig. 7 Directivty patterns obtained for exciation a surface wave with diffrent azimithal angles.

Form verification it can be observed that the pencil beam direction depends on direction of lunching of surface wave. A unwanted radiation in forward direction is mainly due to radiation of the source as well distribution of the surface wave excited along aimed direction, i.e. along the ground plane, at the edge of the ground plane.

Conclusion and future work

In the work was presented the dual band holographic antenna which with mechanical scanning can create conical radiation pattern. For this antenna was proposed excitation to lunch properly surface wave in four directions to make correct transition between surface wave and leaky wave. Also, the project was extended to the concept of flat antenna with variable direction of the pencil beam. With this antenna and double rotator the antenna is able to scan all space i.e. in theta and phi angles.

The purpose of future work is to create dual antenna covering two channels with high focusing without application mechanical scanning for conical beam. Considering variable angle of beam radiation, design needs to apply changes in the finite ground plane and technique of lunching of surface wave.