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High-Gain Omnidirectional Radiation Patterns from a Metal Strip Grating Leaky-Wave Antenna

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Introduction

The metal strip grating (MSG), i.e., a periodic planar arrangement of parallel metal strips of infinite length and infinitesimal thickness, is a canonical periodic structure that finds many applications in electromagnetic radiating and waveguiding devices. In particular, by placing a MSG above a ground plane, and possibly inserting a dielectric slab in between, a simple but effective leaky-wave antenna can be designed, as first proposed by Honey in the 1950s [1] and then studied by different authors with many variations [2,3].

Recently, the possibility to achieve highly directive radiation from simple sources embedded in grounded slabs made of artificial materials has been investigated and related to the excitation of leaky waves [4,5]. Furthermore, in [5] the radiation of almost-omnidirectional pencil beams pointing at broadside or conical beams scanned off broadside has been reported for a grounded wire-medium slab excited by a dipole source. This has been explained in terms of the excitation of a cylindrical leaky wave having isotropic propagation features as a consequence of the spatial dispersion of the homogenized medium.

In this work we aim at showing that highly directive but nearly omnidirectional beams are obtained by employing a grounded slab made of an *ordinary* homogeneous material (air is used here) covered with a MSG and excited by a horizontal electric dipole source. An approximate homogenized network representation of the MSG, which takes into account its spatially dispersive nature, allows us to analytically prove that the wavenumber of the dominant leaky wave is independent of the azimuthal propagation angle. As a result, the radiated beam is almost omnidirectional, as confirmed by rigorous simulations of the actual periodic structure performed with the method of moments.

Transverse Equivalent Network and Isotropic Modal Propagation

The structure considered here, i.e., a MSG placed in air above a perfectly conducting ground plane and excited by a horizontal electric dipole parallel to the strip axis (x direction) at a height h_s above the ground plane, is shown in Fig. 1(a)

together with the relevant geometrical and physical parameters. By a customary application of reciprocity theorem, the far field radiated in the (θ, ϕ) direction can be evaluated by determining the electric field E_x produced at the source location by a plane wave impinging on the structure from the same direction. Since the dipole is directed parallel to the x axis and the strips are embedded in a homogeneous medium (air), a purely TM_x field is excited.

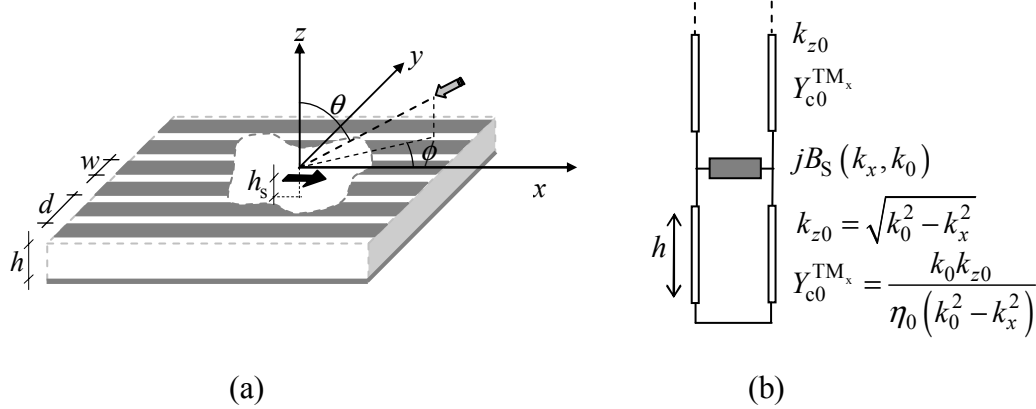


Fig. 1 – (a) Metal strip grating (MSG) above a ground plane, excited by a horizontal electric dipole parallel to the strip axis, with the relevant physical and geometrical parameters; also shown is a uniform plane wave incident from the direction (θ, ϕ) , used in the calculation of the far field radiated by the dipole based on reciprocity. (b) Transverse equivalent network for the problems of plane-wave incidence or of modal propagation at arbitrary angles (TM_x polarization).

Assuming that the period d of the MSG is much smaller than the free-space wavelength $\lambda_0 = 2\pi/k_0$, the effect of the higher-order Floquet modes can be lumped into a single shunt equivalent susceptance B_S , as shown in Fig. 1(b) (where $k_x = -k_0 \sin \theta \cos \phi$). An approximate expression for B_S can be derived from the generalized Sakurai-Vainshtein-Sivov boundary condition for the averaged fields of the zero-th order space harmonic (see [7]) and is

$$B_S(k_x, k_0) = \frac{2\pi}{\eta_0} \frac{k_0}{d(k_0^2 - k_x^2) \ln \csc\left(\frac{\pi w}{2d}\right)}, \quad (1)$$

where η_0 is the characteristic impedance of free space. The susceptance in (1) depends on both the frequency and the spatial wavenumber k_x , i.e., it is both temporally and spatially dispersive. A more involved expression for B_S can be found in the Waveguide Handbook for the case $k_x = 0$, i.e. $\phi = 90^\circ$ (see [7], p. 286).

The dispersion equation for TM_x modes propagating at an arbitrary angle ϕ along the structure can be obtained by enforcing the condition of resonance on the transverse network in Fig. 1(b), where now $k_x = k_\rho \cos \phi$ and $k_\rho = \beta - j\alpha$ is the modal wavenumber (which is complex for leaky modes). Assuming that k_ρ (and hence k_{z0}) is not a function of angle ϕ , it is required that the functional

dependence on k_x exhibited by B_S and $Y_{c0}^{TM_x}$ be the same in order to have a solution that does not depend on ϕ . It is seen from (1) that this is indeed the case. This proves that the wavenumber of a TM_x mode does not depend on its azimuthal direction of propagation, i.e., modal propagation is *omnidirectional*. As shown next, the radiation from such an omnidirectional cylindrical TM_x leaky waves excited by a dipole source is also omnidirectional.

Numerical Results

In this section numerical results are given for the radiation pattern of the structure shown in Fig. 1(a), calculated by reciprocity. In particular, a comparison is presented between the approximate model based on a homogenization of the MSG and its representation through an equivalent temporally and spatially dispersive susceptance (see Eq. (1)) and a full-wave analysis based on the method of moments. The latter uses a periodic Green's function to enforce the electric field integral equation on the strip conductor in a unit cell of the structure. The periodic Green's function is accelerated by using the Ewald method.

In Fig. 2 radiation patterns are shown for a structure as in Fig. 1(a) with $d = 1$ mm, $w = 0.5$ mm, $h = 7.439$ mm (this value for h maximizes the power density radiated at broadside at $f = 20$ GHz [8]), and $h_S = h/2$ at two different frequencies, $f = 20$ GHz and $f = 20.5$ GHz. In both cases, very good agreement is seen between the homogenized and full-wave results.

At $f = 20$ GHz an almost omnidirectional pencil beam pointing at broadside is obtained (see Fig. 2(a)). By increasing the frequency, the pattern scans and an omnidirectional conical beam is obtained (see Fig. 2(b), where the scan angle is approximately 13°). In both cases the far field is mainly due to the dominant TM_x leaky wave whose radiation is almost omnidirectional, as expected.

Conclusion

Radiation features of a horizontal electric dipole placed between a metal strip grating and a perfectly conducting ground plane have been investigated; in particular, approximate results obtained by representing the grating through an equivalent homogenized surface impedance and full-wave results obtained with the method of moments have been presented. Both models show that by properly designing the structure, narrow omnidirectional pencil beams pointing at broadside can be obtained as well as narrow omnidirectional conical beams pointing at some scan angle. This is due to the excitation of a weakly-attenuated cylindrical leaky wave, TM with respect to the strip direction, whose wavenumber is independent of the azimuthal propagation angle thanks to the spatially-dispersive nature of the equivalent surface impedance of the metal strip grating.

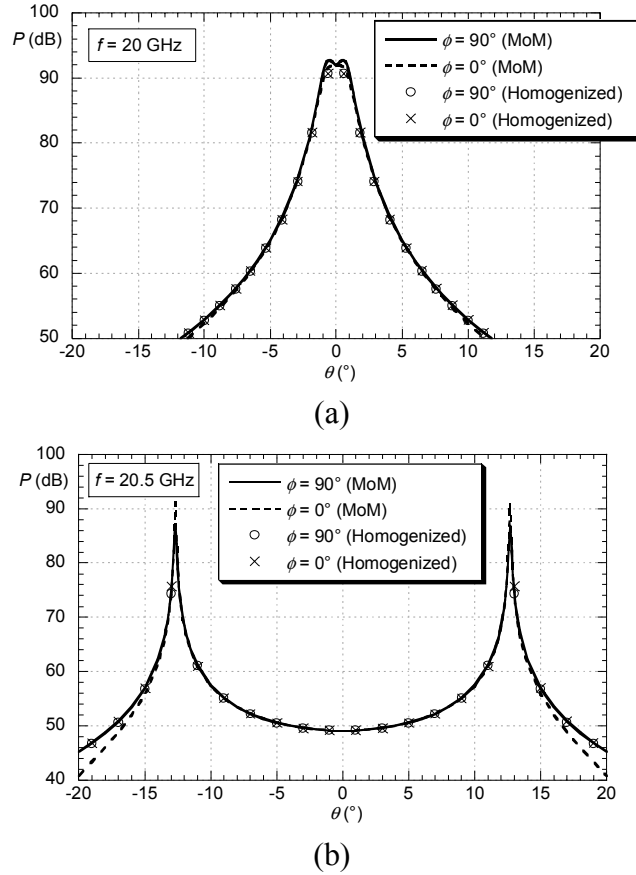


Fig. 2 – Normalized radiation patterns for a horizontal electric dipole between a ground plane and a MSG as in Fig. 1(a), at (a) $f = 20$ GHz and (b) $f = 20.5$ GHz. Parameters: $d = 1$ mm, $a = 0.5$ mm, $h = 7.439$ mm, $h_s = h/2$.

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