Enhanced radiation from an electrically small antenna using sub-wavelength metal strip grating

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Abstract

This article reports the radiation performance enhancement of an electrically small antenna using sub-wavelength metal strip grating, in the microwave frequency regime. The sub-wavelength grating converts the high spatial-frequency components of radiation emitted from an inductor loaded truncated-ground open coplanar antenna into a low spatial far-field spectrum. The spectral conversion results in enhanced efficiency and radiated power gain in the S-band corresponding to TE polarization. The gain of the antenna is enhanced from $-9.74$ dBi to $1.6$ dBi for TE polarization. The prototypes are fabricated in-house and the design is validated experimentally.

1. Introduction

Evanescent to propagating wave conversion is an intriguing research topic over the decades. An electromagnetic source generates both regular propagating and evanescent waves. The later one contains sub-wavelength information about the source and it decays exponentially as the wave moves away from the source. This accounts the reason behind Abbe’s diffraction limit of an optical microscope [1]. Super-resolution could be achieved by converting the evanescent wave into a far-field propagating wave. The near-field microscopes utilize dielectric micro-spheres and periodic-dielectric cylinders near the source for efficient spectral conversion [2, 3]. The invention of metamaterials has boosted the research on near-field manipulations and Pendry et al showed that a negative refractive index slab, with constitutive parameters $\epsilon = \mu = -1$, could restore the evanescent spectra of the source through evanescent-amplification and acts like a perfect lens [4]. Pendry also showed that sub-wavelength gratings could be used for near-field imaging in TM polarization by exciting surface plasmon resonance [5]. In the microwave regime, evanescent filtering of low spatial components is successfully implemented for near-field imaging under TE incidence [6]. The fundamental working principle behind such near-field super lens is their ability to transport evanescent spectrum emitted by the source and hence it can be used for numerous applications like high density optical lithography, sub-wavelength sensing, Nano-fabrication etc. A variety of studies have been focused on this topic in the optical regime [7]. The operation of such super lenses are limited within the near field of the source. In order to avoid this disadvantage, the concept of Far Field Super Lens (FSL) was introduced and by the use of which the evanescent near field can be converted into far-field propagating wave [8]. Sub-wavelength gratings have been effectively used for converting the near field angular spectrum emitted from an object into far-field spectrum [9, 10].

One should note that an Electrically Small Antenna (ESA) has all its energy concentrated on its reactive near-field, which severely affects its radiation efficiency. This near-field can be perturbed using periodic inclusions so that the reactive field can be converted into a propagating far-field. Ziolkowski used the concept of covering an ESA with a double negative metamaterial sphere for radiation enhancement [11]. The highly capacitive reactance of the ESA could be resonantly matched with the inductance offered by the Double Negative metamaterial cover. Eleftheriades et al used the evanescent to propagating wave conversion behavior of sub-wavelength gratings for enhancing the radiation performance of an invisible source [12]. He also achieved efficient radiation from an array of invisible point sources using sub-wavelength gratings [13].
In this paper, the spectral conversion offered by a sub-wavelength metal strip gratings is utilized for enhancing the radiation performance of an electrically small antenna. Both TE and TM polarizations are allowed to impinge on the grating and it is shown that TE polarization can significantly enhance the radiation efficiency and gain of the antenna. The designs are computationally analyzed using the CST Microwave Studio and experiments are conducted using the Agilent PNAE8362B network analyzer. This paper is organized as follows. Section 2 deals with the theory of sub-wavelength metal strip gratings and the radiation characteristics of the reference inductor loaded ESA. The results of detailed simulation studies performed under TE and TM polarizations are included in section 3. The simulation results are experimentally validated inside an Anechoic chamber and are given in section 4.

2. Theory and geometrical specifications

2.1. The electrically small radiator

The power radiated from an elementary electrically small dipole can be represented as [11],

\[
P = \eta \left( \frac{\pi}{3} \right) \frac{I_0}{\lambda} \left[ 1 - j \frac{1}{(kr)^2} \right]
\]

where \( \eta \) is the wave impedance, \( I_0 \) is the driving current, \( l \) is the length of the antenna, \( k \) is the wave number and \( \lambda \) is the operating wavelength. This radiator has a capacitive near-field, and the reactance ratio is much lesser than one. This highly capacitive reactive power limits the radiation efficiency of an electrically small antenna. It is interesting to note that the near-field reactive energy can be converted into regular propagating one by placing the ESA near a sub-wavelength grating. The grating will perform spatial Fourier Transform operation and will convert the incident spatial-spectrum into weighted output spectrum shifted in wave number by an integer multiples of grating wave number as [13],

\[
E_{\text{out}}(k_x) = \sum_{n=-\infty}^{\infty} E_{\text{in}}(k_x - \frac{2\pi n}{L}) B_n \left( k_x - \frac{2\pi n}{L} \right)
\]

where \( E_{\text{in}} \) is the input spectrum of the incident wave, \( B_n \) is the weighting function dependent upon the geometry of grating and \( L \) represents the period. It states that the output spectrum is the weighted copies of input-spectrum shifted by an integer multiples of grating wave number \( 2\pi/L \). This means that proper selection of the input reactive spatial spectrum and grating period can convert the reactive near-field into low spatial spectrum.

The peculiarity of electrically small radiators is that its near-field contains high spatial oscillations and hence the radiation efficiency will be poor. The ESA taken here for investigation is the inductor loaded open coplanar wave guide antenna [14]. For the experimental realization of spectral conversion, the antenna under test is loaded over the metal strip grating. The width of grating metalization is denoted by \( W_1 \) and the slit width is denoted by \( W_2 \). Geometry of the proposed antenna is depicted in figure 1. Figure 1(a) describes the geometrical specifications of the reference inductor loaded coplanar wave guide fed antenna. It occupies an area of 0.08\( \lambda_0 \times 0.0479\lambda_0 \) and at the resonant frequency, the \( ka \) value is 0.2924 which is much smaller than the Chu-limit. It comprises of a simple Open Coplanar Waveguide with one end of the center conductor soldered with a chip inductor of 23 nH on to the top base metalization. Microwave signal is fed using a standard SMA connector soldered to the lower bottom end of the Coplanar Waveguide as shown in figure 1(a). The dimensions of the antenna are \( P_b = 0.8 \text{ mm}, P_w = 1 \text{ mm}, P_h = 0.8 \text{ mm}, L_p = 4 \text{ mm}, W_g = 3 \text{ mm} \). The antenna is fabricated on a low-cost Copper clad epoxy substrate of dielectric constant 4.4 and thickness \( h = 1.6 \text{ mm} \). The grating loaded final antenna configuration is depicted in figure 1(b). The antenna and grating are fabricated using the standard photo-lithographic fabrication techniques. The photograph of the fabricated prototype is shown in figure 1(c).

2.2. Radiation characteristics of the reference electrically small radiator

The radiation performance of the fabricated ESA is tested in an Anechoic chamber using the vector Network analyzer. The reflection and near-field characteristics of the reference antenna are given in figure 2. Resonance is found to be at 2.37 GHz and the reflection coefficient value is \(-20 \text{ dB} \) at resonance. The 2:1 VSWR bandwidth \( | S11 | < -10 \text{ dB} \) is 2% around the resonant frequency. The simulated near-field electric-field distribution on the antenna structure is shown in the inset of figure 2(a). Resonance is attributed due to the monopole excitation on the antenna structure. The opposing \( E_x \) components of the electric fields cancel each other at the far-field and radiation is attributed due to the \( E_y \) component of the electric field and hence polarization of the antenna is lying along x-axis. The transmitted spectrum just above the antenna structure is depicted in figure 2(b). The spectrum has been normalized with respect to the maximum amplitude of spectral component present. One could see that the radiated spectrum contains two high-spatial propagating components and the low-spatial ones are...
extremely weak in magnitude. The presence of dominant high spatial transverse oscillations makes the contribution of reactive power in the near field of the antenna. It is to be noted that the low spatial components are responsible for far-field radiation and since it is weak in magnitude, the proposed prototype is not an efficient radiator. The low spatial electromagnetic wave contain an in-phase electric and magnetic fields, contributing real radiated power from the source whereas in high spatial fields, there exists temporal phase shift between electric and magnetic fields contributing reactive power. Radiation efficiency can be improved by converting the high spatial components into low spatial propagating ones using a sub-wavelength grating with optimized period. Physically, this is equivalent to reducing the phase shift between electric and magnetic fields radiated by the antenna. For efficient spectral conversion, the grating period should be $K_x = 15.75/\text{mm}$ such that the grating parameters are $W_1 = W_2 = 0.2\ \text{mm}$. But due to the practical limitations associated with the photo-lithographic fabrication procedures, we have selected the parameters as $W_1 = W_2 = 0.6\ \text{mm}$.

The simulated radiation patterns of the antenna without the grating at resonance are plotted in figure 3. The simulated 3D gain pattern of the antenna at resonance is shown in figure 3(a). The antenna shows omnidirectional radiation pattern and the polarization is directed along the $x$-axis. The simulated gain is found to be only $-9.74\ \text{dBi}$ at resonance. The measured gain, calculated using the standard gain comparison method, is found to be $-9.6\ \text{dBi}$. The E-plane and H-plane co-polar patterns of the antenna at resonance are illustrated in figure 3(b). The cross polar isolation is $-15\ \text{dB}$ for the E-plane and $-13\ \text{dB}$ for the H-plane. Radiation efficiency of the antenna is calculated using the Wheeler Cap method and is found to be 13% at resonance.

Figure 1. Geometrical specifications of the antennas. (a) Inductor loaded Open coplanar reference antenna, (b) Sub-wavelength grating loaded antenna and (c) photograph of the fabricated antenna.

Figure 2. Characterization of the reference antenna (a) Reflection coefficient with resonant electric-field in the inset and (b) Transmitted spatial frequency above the surface of the antenna at resonance with photograph in the inset.
3. Results and discussions

3.1. Sub-wavelength grating loaded design: TE polarization

The radiation efficiency and radiated power could be significantly enhanced by converting the high-spatial spectral components in the near-field into low-spatial frequencies. This could be easily achieved by placing the antenna near a sub-wavelength metal strip grating. The grating will perform spectral conversion resulting in highly efficient radiation from the source. Geometry of the proposed grating backed dipole antenna under TE incidence is shown in figure 1(b). The grating occupies an overall area of $60 \times 60$ mm$^2$ and contains 40 metallic strips. In TE polarization, the incident electric field is oriented parallel to the grating metalization. Initially, the effect of loading height $h_1$ on the radiation characteristics of the antenna is studied. Parametric simulations are performed using CST Microwave studio for optimizing the loading height. It is observed that the variation in loading thickness has no significant effect on the resonant frequency and impedance matching performance of the antenna. But it is interesting to observe that the variation severely affects the radiated power from the antenna. The effect of variation in radiation patterns with loading height is depicted in figure 4. It is clear that placing the antenna near the grating enhances the radiated power. For a lower loading height ($h_1 = 30$ mm), the radiation patterns contains no side lobes and a broadside pattern could be achieved. The corresponding 3dB beam widths are $76^\circ$ for the E-plane and $120^\circ$ for the H-plane. This configuration gives maximum radiated power along the broadside direction. Increasing loading height further reduces the transmitted power gradually along the broadside direction resulting in a reduction in radiated gain and efficiency. The enhancement in radiated power from the ESA is the clear indication of efficient spectral conversion. The radiated power along the lower hemisphere of the grating backed configuration is found to be suppressed. This is due to the fact that the grating blocks propagating waves towards the lower hemisphere such that the tangential component of electric field at the grating metal boundary should be zero. The small leakage is attributed due to the negligibly small electric field existing in the dielectric between the grating metal plates. The simulated 3D radiation patterns of the the grating loaded antennas for the three different loading heights ($h_1 = 30$ mm, $h_1 = 50$ mm and $h_1 = 70$ mm) are shown in figures 4(c)–(e).

In order to find the reason behind the variation in radiation patterns, the near fields of the antennas have been taken into consideration. The near-field contains some useful information about the radiation behavior of the antenna. The presence of both propagating and evanescent spatial components could be detected and analyzed by applying spatial Fourier Transform to the near-field electric field distribution [15]. Figure 5 shows the spatial-frequency distribution of the ESA with and without the grating for $d_e = 30$ mm and $d_e = 70$ mm. As expected, the reference spectra contains high-spatial propagating components and low-spatial spectrum is suppressed. As the distance from the antenna is increased, the magnitude of the high spatial component is decreased. Figure 5(b) illustrates the corresponding transformed spectrum and it could be seen that the grating converts the input high spatial spectrum efficiently to the propagating side resulting in broadside radiation coverage. Since the interaction of grating with the high spatial spectrum is decreasing, the antenna shows a weak spectral magnitude for higher loading height and hence the radiated power from the antenna is gradually...
decreased. The radiated gain of the antenna could be further increased by using a finer sub-wavelength grating with a lower grating period.

3.2. Sub-wavelength Grating loaded design: TM polarization

Parametric analysis has also been performed for TM polarization and the effect of variation in radiation characteristics with loading height is shown in figure 6. In TM polarization, the antenna is arranged such that the electric-field is oriented perpendicular to the grating metalization. It is to be noted that the impedance matching and resonant characteristics of the antenna remains unaltered similar to that for TE polarization. Under TM polarization, radiation enhancement effect is not achieved and hence the radiation patterns essentially behaves like that of the reference antenna.

4. Experimental characterization

Experiments have been conducted on the fabricated prototypes for both TE and TM polarizations. The fabricated antenna prototype is tested inside an anechoic chamber using PNAE8362B vector network analyzer. The prototypes are fabricated using standard photo-lithographic manufacturing techniques. The measured variation in the reflection characteristics of the fabricated antennas against the loading height for TE and TM polarization are depicted in figures 7(a) and (b). The antenna resonance remain unaltered against the change in loading height for both the polarizations. Radiation patterns are measured in the anechoic chamber using an Ultra Wide band horn antenna as the receiver and the grating loaded antennas as the transmitter. Distance between horn antenna and the antennas under test is set to be 2 m. The test antenna is rotated using a computer controlled turn table assembly and the power radiated around the antennas for two principal planes are recorded. The measured radiation patterns of the antennas are depicted in figures 7(c)-(f). The patterns show fair agreement with the simulation results. Maximum radiated power is observed for \( \text{dz} = 30 \) mm. TM polarization shows no enhancement in the radiated power as compared to the reference antenna. Gain of the antennas are measured using the standard gain comparison method. It is observed that the antenna shows a maximum gain of
1.6 dBi for a loading height of $h_1 = 30$ mm for TE polarization and the corresponding efficiency is found to be 34%. The variation in gain and efficiency with loading height is depicted in table 1.

5. Conclusion

We have presented the radiation enhancement properties of sub-wavelength metal gratings in the microwave regime from an electrically small antenna. Both Transverse Electric and Transverse Magnetic polarizations are studied in this paper. TE polarization shows enhanced radiation performance whereas for TM incidence,
Figure 7. Experimental characterization of the fabricated antennas. Effect of $d_z$ on (a) Reflection characteristics for TE polarization, (b) Reflection characteristics for TM polarization, (c) H-plane radiation pattern for TE polarization, (d) E-plane radiation pattern for TE polarization, (e) E-plane radiation pattern for TM polarization, and (f) H-plane radiation pattern for TM polarization.

Table 1. Measured gain and radiation efficiencies for TE polarization.

| Loading height, $h_1$ (mm) | Measured gain (dBi) | Efficiency (%) |
|----------------------------|---------------------|----------------|
| 30                         | 1.6                 | 34             |
| 50                         | −0.1                | 30             |
| 70                         | −0.61               | 27             |
radiation enhancement is significantly low. The optimum design achieves a gain of 1.6 dBi and efficiency is enhanced to 34% at resonance for TE polarization.

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