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Gain and Bandwidth Enhancement of Slot Antenna Using Two Unprinted Dielectric Superstrate

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Abstract— **This paper presents a high-gain and wideband antenna with a compact, simple and low-profile structure. The design strategy of high gain Fabry-Perot resonator antennas (FPRA), which have a superstrate with increasing phase in the operating band, has been applied to design the antenna. A double-layered unprinted dielectric superstrate is used as a partially reflective surface (PRS) to enhance the gain of the antenna and to produce a reflection phase curve versus frequency with a positive slope. The superstrate is composed of two dielectric slabs, and it is truncated so that its dimension to be about 1.5λ×1.5λ. By using such an unprinted double-layered dielectric, as a superstrate, the bandwidth of about 14.3% can be achieved. To further increase the size of the upper unprinted slab, the gain can be enhanced, without compromising the bandwidth. A prototype antenna has been designed and simulated at 9 GHz. The achieved peak gain is 17 dB.**

Keywords- Cavity antenna, Fabry-Perot antenna, Superstrate, High gain.

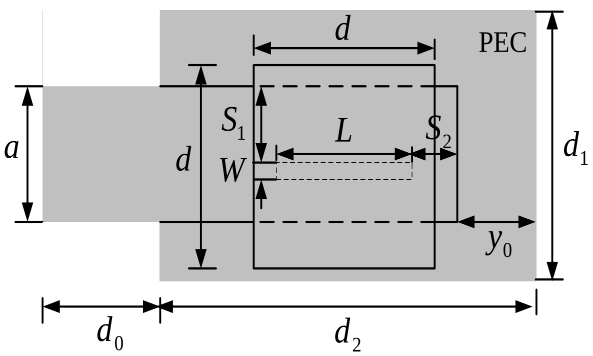
I. INTRODUCTION

The gain of a small antenna such as a patch, dipole or slot, can be enhanced by using a partially reflecting superstrate (PRS). This idea first introduced by Trentini in 1956 [1] and later investigated by Jackson and Alexopoulos in 1985 [2]. Antennas of this nature utilize a resonant cavity formed between a conducting ground plane and the PRS. The excited fields in the cavity undergo multiple reflections at resonance and leak through the PRS in broadside direction as a highly directive beam. Such antennas are known as resonant cavity antennas, two dimensional leaky-wave antennas or Fabry-Pérot resonator antennas. With a planar configuration and simple design, these antennas are considered as a potential replacement for bulkier high-gain antennas, such as horns or reflectors, for a number of exciting applications. Typically, a PRS with high permittivity or high permeability ($\varepsilon \gg 1$ or $\mu \gg 1$) material [2] and a large area [3, 4] is used to achieve strong superstrate reflectivity [5]. The Fabry–Perot cavity antennas are obviously cavity antennas that have been studied for a long time in the microwave community. The Fabry-Perot resonator antenna is a kind of highly directive antenna [5], which is formed by placing a partially reflective surface (PRS) in front of a simple primary radiator with a ground plane. Several applications have been proposed for similar structures such as antennas with the required phase-front and amplitude linearity for helicopter stabilization [6] or tracking systems for missiles [7]. An exhaustive source about the theory, design and practical applications of the cavity-type antennas can be found in [8]. Recently, it has been proposed to design cavity antennas with no uniform mirrors to obtain very low side lobes [9]. More recently, Fabry-Perot resonator antennas (FPRAs) attract researcher's attention [10-14], due to their advantages of high gain; simplicity, low cost, etc. Recently, a new waveguide slot antenna has been proposed that considerably improve the antenna specifications using radiating surface [15]. Also, in [16] a thick unprinted dielectric slab of quarter-wavelength is located above a slot antenna to achieve concurrently high gain and large bandwidth. In [17] a wideband resonant cavity antenna (RCA) with circular polarization has been proposed with high-gain performance. The main beam of a Fabry-Perot cavity antenna produces side-lobes which are proportional to the scan angle. An alternative mechanism using dielectric-ferrite superstrate has been proposed to control side-lobe level [18].

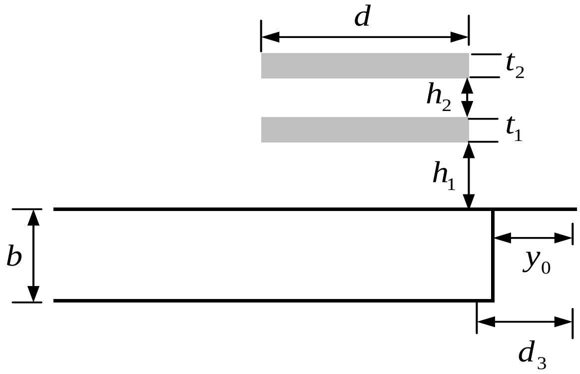
In this paper two simple unprinted dielectric slabs with the same side dimensions and different thickness have been used as superstrate to improve the antenna gain and bandwidth, over a wide frequency band, so that, a slotted antenna which is excited by a rectangular waveguide, has been used as the primary radiating source.

II. ANTENNA DESIGN

The configuration of the proposed high-gain slot antenna is shown in Fig. 1. The superstrate is composed of two square dielectric slabs which have same side lengths of d and thickness of t_1 and t_2. The lower superstrate is symmetrically placed above the slot plane (as the ground plane) at a given height. There is an air gap between the two slabs, whose height is h_2. Each dielectric layer is assumed lossless, homogeneous, and isotropic. A Fabry-Perot cavity is formed by the superstrate and a PEC ground (slot plane). The separation area between the PEC and the superstrate is considered free space and the height is h_1.



(a)



(b)

Fig. 1. Configuration of the proposed waveguide slot antenna (a) Top view (b) Side view

A rectangular waveguide WR90 is used to feed the Fabry-Perot Cavity Antenna. A rectangular slot was made in a 1 mm-thick copper ground plane and dimensions of slot are: L =18 mm and W = 3.5 mm. The design of the antenna starts from that of the superstrate or partially reflective surface. As demonstrated in [10], a superstrate with increasing phase inside the operating band might lead to a wideband Fabry-Perot resonator antenna. According to the ray-tracing analysis in [1], the reflection phase of the PRS required for maximum broadside radiation at the resonance frequency can be formulated as

$$\rho_H = \frac{4\pi h}{c} f + (2N-1)\pi \qquad (1)$$

Where h is the cavity thickness, f is the operating frequency, N=1, 2, … is an integer number and c is the light velocity in free space. If reflection coefficient of the superstrate is $\rho\exp(j\psi)$ and f(α) is the normalized field pattern of feed antenna, then normalized electric field E and power S at an angle α to the normal is derived in [10].

$$|E| = \sqrt{\frac{1-\rho^2}{1+\rho^2-2\rho\cos\varphi}}\, f(\alpha)\ ,\quad S = \frac{1-\rho^2}{1+\rho^2-2\rho\cos\varphi} f^2(\alpha) \qquad (2)$$

Where, φ is the phase difference between waves reflecting from PRS. Bore sight gain (θ =0°) and bandwidth is function of reflection coefficient [1]:

$$G = \frac{1+\rho}{1-\rho} \quad BW = \frac{\Delta f}{f_0} = \left(\frac{\lambda}{2\pi l_r}\right)\frac{1-\rho}{\rho^{0.5}} \qquad (3)$$

For the waves reflecting from PRS to be in phase in normal direction, resonant distance L_r between ground plane and PRS is given by [1].

$$L_r = \left(\frac{\psi_0}{360} - 0.5\right)\frac{\lambda}{2} + N\frac{\lambda}{2} \qquad (4)$$

Where ψ_0 is phase angle of reflection coefficient of the PRS in degree and N is a non-negative integer number.

The design frequency band in this work is considered to be in frequency range of 8.4-9.7 GHz. In the design procedure (which will be explained in detail by parametric study in this section), the permittivity of two slabs is chosen to be ε_1=6.15 (lower slab) and ε_2=2.2 (upper slab). The thicknesses of slabs are 2.916 mm and 5.5 mm, respectively, and parameter h_2 is 6.2 mm. Fig. 2 and Fig. 3 shows the reflection magnitude and the gain of the proposed antenna with and without PRS (conventional one), respectively. The peak gain is about 17 dBi.

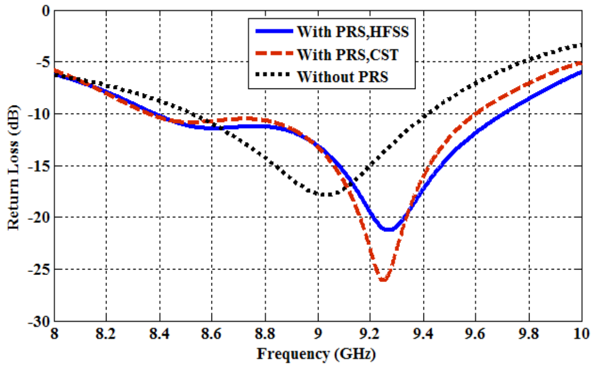


Fig. 2 Simulated return loss of the proposed waveguide slot antenna compared with conventional one. Proposed antenna: a=22.86 mm, b=10.16 mm,d_0=20 mm, d_1=95 mm, d_2=67.5 mm, d_3=33.72 mm, y_0=30 mm, L=18 mm, W=3.5 mm,S_1=1.68 mm,S_2=3.72 mm, d=50 mm,h_1=19.4 mm,h_2=6.2 mm,t_1=2.91 mm,t_2=5.5 mm.

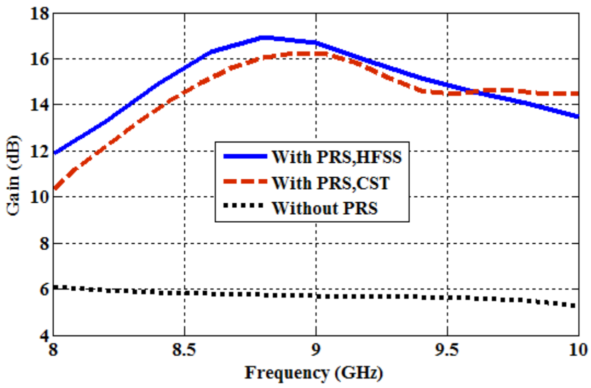
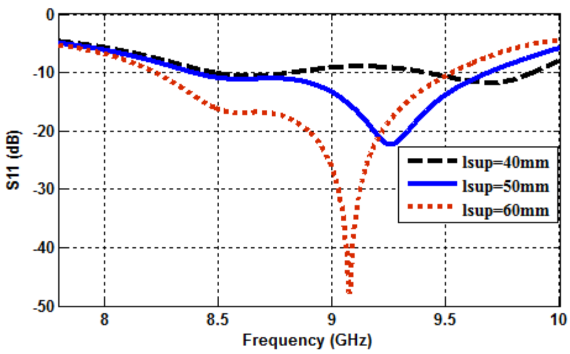


Fig. 3 Simulated gain of proposed waveguide slot antenna compared with conventional one.



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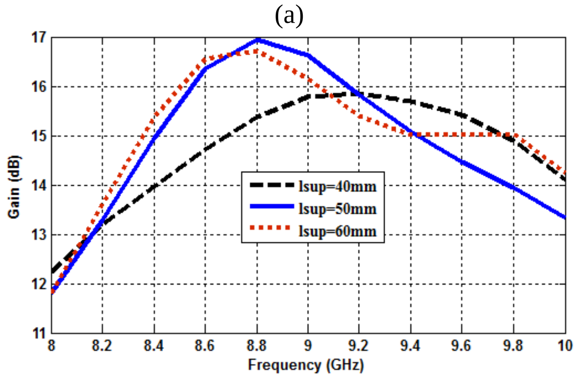
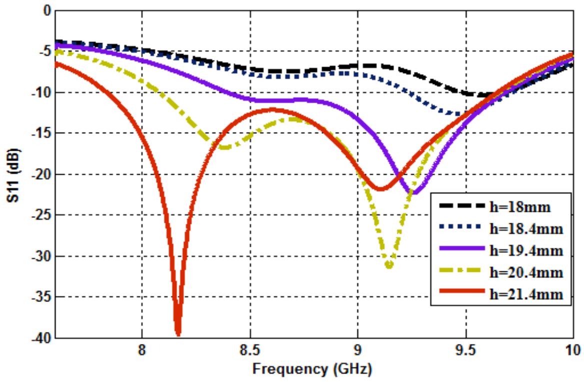


(b)

Fig. 4 Return loss and gain of the proposed antenna for a set of superstrate length values



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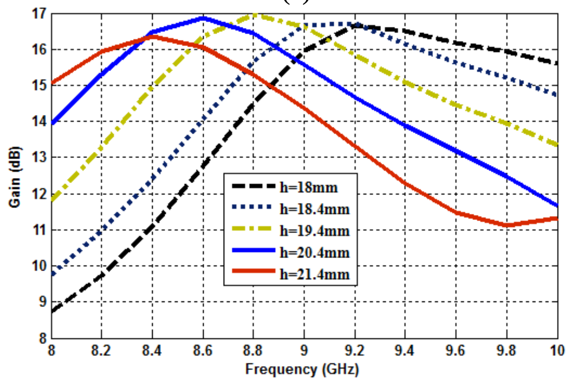


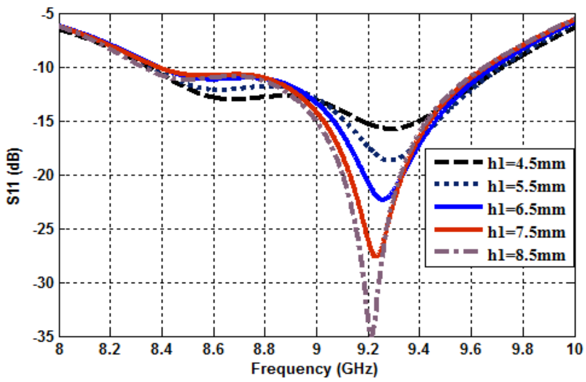
(b)

Fig. 5. The return loss and the gain of the proposed antenna for a set of superstrate height values. (a) Return loss (b) Gain.

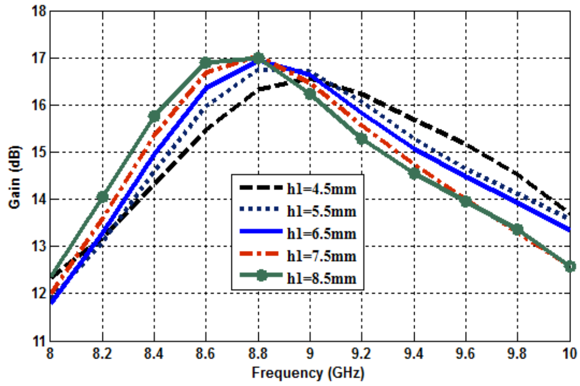
Fig. 4 shows the return loss and the gain of the proposed antenna, for a set number of superstrate length values.

It has been shown in Fig. 4 that antenna bandwidth can be approximately enhanced by reducing the size of the PRS [11, 14]. It also can be found that the gain will decrease while the antenna bandwidth will increase with decreasing the size of PRS. The designed FPRA has been used to study the relation of the bandwidth and the directivity by gradually reducing the size of the PRS. The designed PRS is applied to form a FPRA. Apparently, a wideband high-gain FPRA is obtained. It was also found that the optimum gain and the bandwidth are obtained when the size of the square slabs is about 1.5λ×1.5λ.

Fig. 5 shows the return loss and the gain of the proposed antenna, for a set number of superstrate height values.



(a)



(b)

Fig. 6. Return loss and gain of the proposed antenna for different values of space between PRSs (a) Return loss (b) Gain.

Fig. 5 depicts that antenna bandwidth can be significantly enhanced by increasing the size of the PRSs. It also can be found that the antenna peak gain shifted to lower frequency with increasing the superstrate height. As it is observed from Fig. 5 (a), parameter *h*, has more effect on the first resonant frequency compared to the second one that confirms the fact that the first resonant frequency (8.2 GHz) is related to cavity and second resonance frequency due to slot.

Fig. 6 shows the return loss and the gain of the proposed antenna for different values of space between PRSs. It shows that by increasing the distance between dielectrics, the gain slightly increased, but to achieve compact size, the distance between the dielectric is selected to be h_1= 6.5 mm.
Fig. 7 shows the effects of the extended broad wall size of the antenna (ground size) on the antenna peak gain.

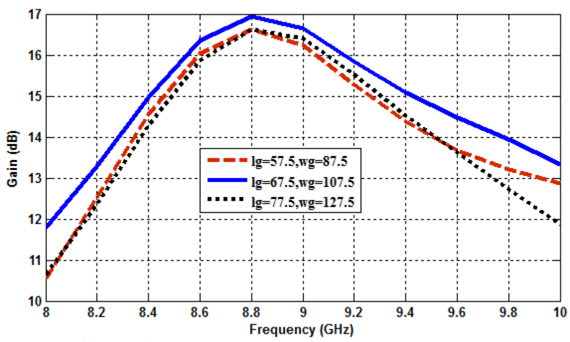
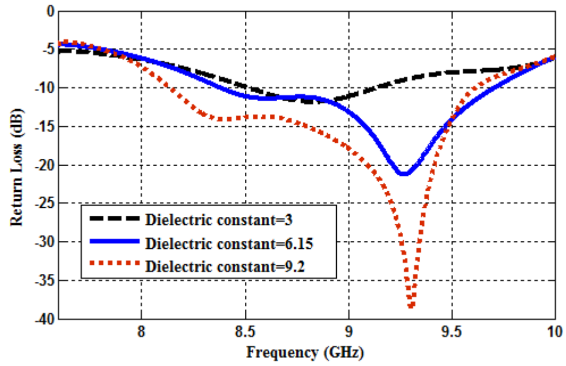
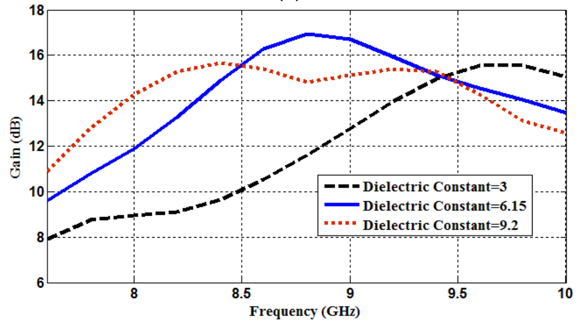


Fig. 7. Effects of ground size on the proposed antenna gain.

As it can be seen from Fig. 7 for lg=d2=67.5 mm, wg=d1=107.5 mm, the proposed antenna has maximum gain. Fig. 8 shows the return loss and the gain of the proposed antenna for different dielectric constant of PRS 1(lower PRS).
As can be seen from Fig. 8, although antenna bandwidth slightly increased with increasing in dielectric constant but for ε_1=6.15, the proposed antenna has maximum gain, so, dielectric constant for lower PRS is selected to be 6.15.



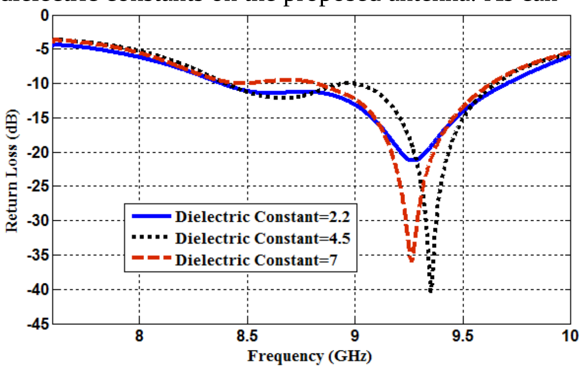
(a)



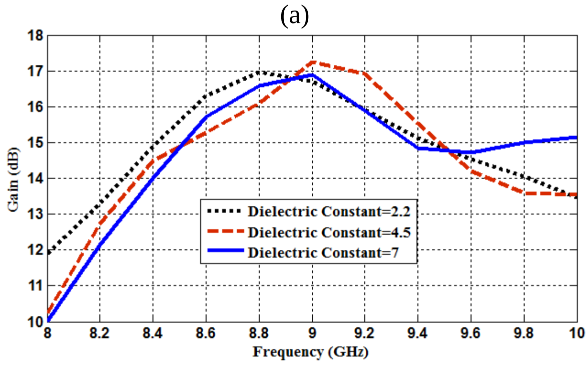
(b)

Fig. 8. Effects of PRS 1 various dielectric constant on the proposed antenna (a) Return loss (b) Gain.

Fig. 9 shows the effects of PRS2 with various dielectric constants on the proposed antenna. As can



(a)



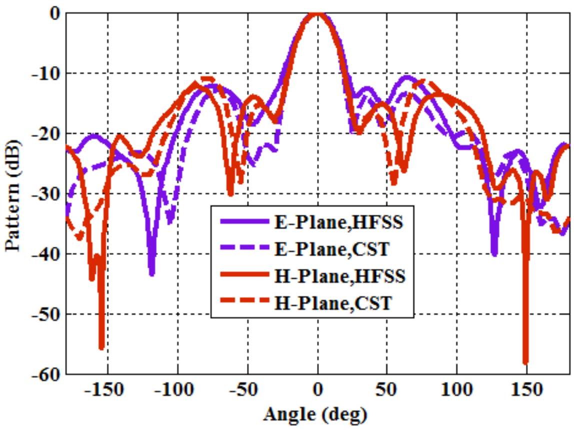
(b)

Fig. 9. Effects of PRS 2 with various dielectric constants on the proposed antenna (a).return loss (b). Gain.

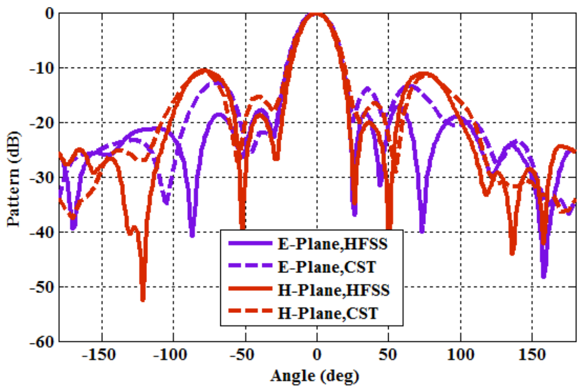
be seen from Fig. 9 bandwidth and gain of the proposed antenna for different dielectric constants of PRS 2, is same, therefore considering the price and ease of preparation, dielectric constant for PRS2 is selected 2.2. The radiation patterns of the antenna in the E- and H-planes at three different frequencies, within its bandwidth, are shown in Fig. 10. It is noted that the side lobe levels are below −10 dB from 8.6 to 9.3 GHz and tend to increase above -10 dB as the frequency increases.

In the antenna design, the size of the two slabs are 50mm × 50 mm × 2.916 mm and 50 mm × 50 mm × 5.5 mm, respectivity. The heights (h1 and h2) of two air gaps are 19.4 mm and 6.2 mm, respectively. The size of the ground is 67.5 mm × 95 mm.

Fig. 11. depicts the radiation efficincy of the proposed antenna that is over 98%.



(a)



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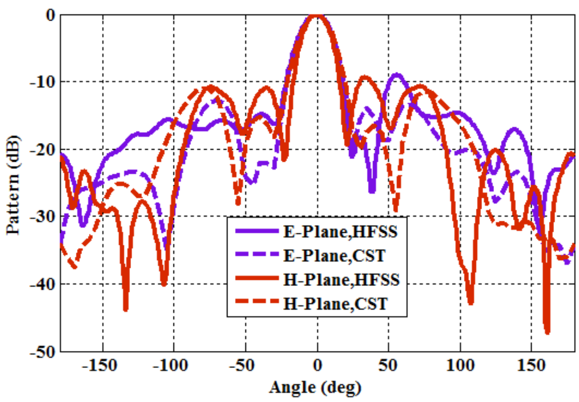

(c)

Fig. 10. Radiation patterns of antenna: (a) 8.6 GHz, (b) 9 GHz, (c) 9.3 GHz

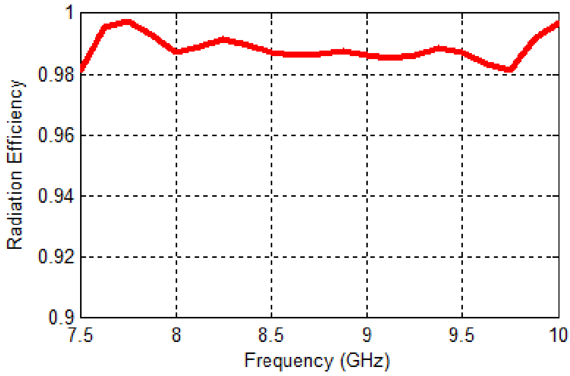

Fig. 11. Radiation efficiency of the proposed antenna

III. CONCLUSION

The proposed antenna is designed to verify its high gain performance. Commercial software HFSS is used to carry out the simulations. The antenna consists of a PEC ground, a PRS, which is composed of two slabs with different thickness, permittivity, and a feed. The simulated good impedance matching, determined by |S11|<-10 dB, is obtained from 8.4 GHz to 9.7 GHz. The gain of the slot antenna is enhanced over a wide-frequency band validating the feasibility of using a simple PRS with small area.

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