Generation of Frequency Steerable Endfire Radiations out of an Spoof-surface Plasmon Polariton E-plane Transmission Line

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Abstract

This paper presents an antenna that generates a frequency steerable endfire electromagnetic radiation out of a spoof surface plasmon polariton (SSPP) transmission line mounted in the center E-plane of a rectangular waveguide. The SSPP transmission has both its upper edge and lower edge patterned with corrugated metal slot/gap arrays of the same period. However, the slot depth on the corrugated pattern along the upper edge is different from the slot depth on the corrugated pattern along the lower edge. This arrangement creates a difference in surface impedance between the upper corrugated edge and the low corrugated edge on the SSPP transmission line, thus allowing the angle of the endfire radiation to be shifted upwards and downwards. According to our simulation, the angle of endfire radiation can be shifted by at least 10 degree simply by varying the operating frequencies.

I. Background

This paper presents an antenna that generates a frequency steerable endfire electromagnetic radiation out of a spoof surface plasmon polariton (SSPP) transmission line mounted in the center E-plane of a rectangular waveguide.

An ideal endfire antenna is an antenna which generates an electromagnetic beam in the forwards direction. Instead of radiating the same intensity of all electromagnetic energy in all directions, which is in general the case in all isotropic antennas, an ideal endfire antenna focus all the energy in the forwards direction only, thus offering superior antenna gain in the direction of choice. A non-ideal endfire antenna is the one which generates a forward beam (also known as an endfire radiation) together with certain extent of broadside radiations in the form of side lobes. Most published endfire antennas belong to the latter category. One such a non-ideal endfire antenna is categorically known as Vivaldi antenna. A Vivaldi antenna transmits the concentrated electromagnetic energy from the slot between two half-wave dipoles. The characteristic impedance of the slot gradually increases until it matches the characteristic impedance of free space. A typical Vivaldi can generate a directional endfire radiation with a gain below 10 dBi over a moderately wide bandwidth. The main reason for such a low gain is because the whole metallic body of a Vivaldi antenna can be a radiator of electromagnetic energy to all directions. The actual radiation pattern of a typical Vivaldi antenna can be full of side lobes and the amount of electromagnetic energy available for the endfire radiation can be very limited. The gain of a typical Vivaldi antenna is always less than 10 dBi, in part because a large portion of the radiation energy is wasted in the side lobes.

Recently, a fundamentally new concept of endfire antenna has been proposed by Kandwal et al [5]. Instead of using two half-wave dipoles, the new endfire antenna proposed has successfully generated an endfire radiation with a gain of about 8 dBi in the neighborhood of 8 GHz out of a spoof surface plasmon polariton (referred hereafter as SSPP) transmission line of three-quarter wavelengths. This antenna used a coplanar to SSPP transition which accepts electromagnetic energy from a coaxial cable in the form of TEM mode. Inevitably, this coplanar to SSPP transition encourages excitation of higher order modes which are fast modes (or leaky modes) contributing to broadside radiations. Whilst this antenna has clearly achieved what a conventional Vivaldi antenna does, a lot of electromagnetic energy loss in the form of side lobes has been observed. The results of our investigation suggest that the radiation loss has happened mainly in the second order modes in the region closed to the aforementioned coplanar to SPP transition. The original paper has also focused unnecessarily on higher orders, which has nothing to do with generation of endfire radiations.

In the view of the above-mentioned problems, it is the an object of the present presentation to report a fundamentally new methodology which permits generation of a highly directional endfire radiation out of a spoof surface plasmon polariton with minimum side lobes and without occupying an excessively large area. This work extends the idea proposed in [5]. In this work, however, the side lobes were completely suppressed by replacing coplanar-to-SSPP transition with a waveguide-to-SSPP transition housed inside a rectangular waveguide. The side lobes were suppressed because of the following reasons: a) The printed circuit of the endfire antenna in the present presentation is mounted one the center E-plane of the rectangular waveguide, where the second order modes are almost non-existent [1-4]. b) The metal wall of the rectangular waveguide blocks off all the broadside radiations and polarizes the electromagnetic energy into transverse electric modes.

Our simulation results suggest that the endfire antenna mounted on the center E-plane of a waveguide can easily generate an endfire radiation with a substantially improved gain [1-4]. Whilst this mechanism is easily understandable even without electromagnetic simulations, the main novelty of this work is ability to generate a frequency steerable endfire radiation out of the same structure by changing the geometry of the printed circuit.

II. Basic Construction of the Proposed E-plane Endfire Antenna

Fig. 1 illustrates the isometric view of the proposed E-plane Endfire Antenna. As shown in Fig. 1, the E-plane endfire antenna contains a rectangular waveguide, an E-plane printed circuit fabricated on an ultrathin substrate. In the rectangular waveguide, the E-plane printed circuit is mounted in line with the plane containing the electric field vector (sometimes called the E aperture) and the direction of maximum radiation. The electric field strength of the incoming polarized electromagnetic wave from the input port is always highest at the E-plane. The antenna accepts electromagnetic in the form of transverse electric mode at input port 1, and generates a substantially focused beam in the direction of endfire radiation. The metallization thickness of the E-plane printed circuit must be thick enough for the whole circuit to be self-supporting. On the other hand, the substrate thickness should be minimized in a way that the E-plane circuit does not cause any reflection against incoming or outgoing electromagnetic energy. When the operating frequencies are below 100 GHz, the thickness of this ultrathin substrate should be as close to 100 microns as possible.

For the purpose of illustration, the E-plane printed circuit shown in Fig.1 contains the most basic version of the SSPP transmission line. In practice, the actual E-plane circuit to be mounted into the waveguide can be varied to some extent.

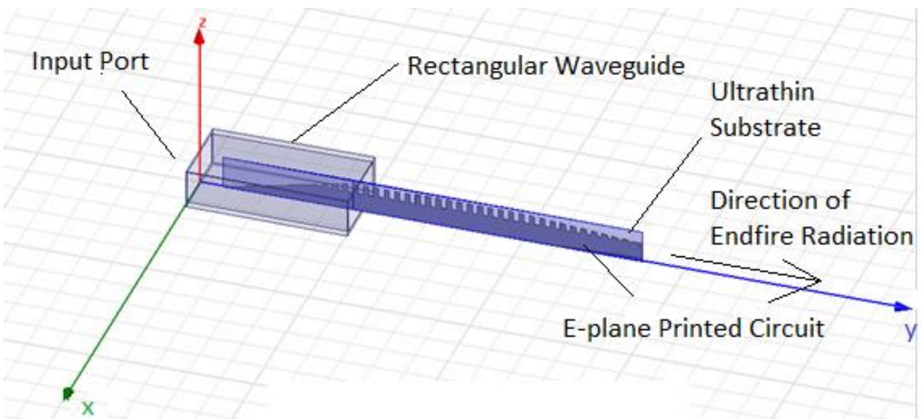


Figure 1. Basic version of the proposed E-plane endfire antenna.

III. The Most Version of the E-plane Printed Circuit

The core of the E-plane endfire antenna in the present presentation is a printed circuit to be mounted on the E-plane of a rectangular waveguide as illustrated in the example in Fig. 2. The printed circuit contains a continuous metal pattern that can be sub-divided into three sections: 1) a waveguide-to-SSPP transition; 2) an SSPP transmission line of one or three quarter electrical wavelengths; and 3) an SSPP-to-waveguide transition. These three sections are explained in the sub-sections which follows:

SSPP Transmission Line: The SSPP transmission line has its upper edge and/or lower edge patterned with periodic corrugated structures, which may be a series of rectangular metal slots and gaps arranged in an alternate manner. In the example as shown in Figs. 1 and 2, only the upper edge of the SSPP transmission line is patterned with a corrugated metal slot array. This SSPP can be partially or completely exposed to air. At frequencies below the cut-off frequency, this SSPP transmission line acts as a slow wave structure in the sense that electromagnetic waves preferentially propagate in the form of a surface mode at a phase velocity below the speed of light, with virtually no radiation loss to the surrounding. At these frequencies, the body of the proposed SSPP antenna is not expected to lose any electromagnetic energy in the form of broadside radiations. With no broadside radiation, the electromagnetic energy propagating along the transmission line is forced to travel in the forwards direction only in the form of a stationary surface wave. However, the electromagnetic energy propagating along the SSPP transmission line can become a leaky mode if it operates at or above the cut-off frequency.

The geometry of each slot/gap pair determines the characteristic impedance of the SSPP transmission line as well as its propagation constant. The slot depth *d* of this SSPP transmission line can be used to find its propagation constant, which in turn can be used to find the group delay or the phase velocity.

$$\beta \approx K_1 \tan\left(\frac{d\varepsilon}{\lambda}\right) \tag{1}$$

where ε is the permittivity of the substrate on which the SSPP transmission line was fabricated and λ is the guided wavelength of the surface mode propagating along the SSPP transmission line. On the other hand, given that the slot width is *s* and the separation between two neighboring slots is *g*, the characteristic impedance of the SSPP transmission line is determined by the ratio of *s/(s+g)* as illustrated by Equation (2).

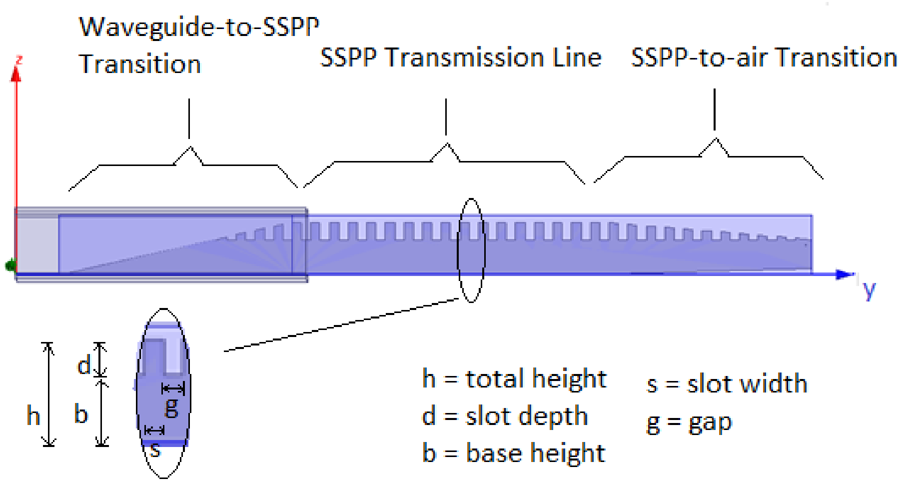
$$Z_o \approx \frac{30\pi}{\sqrt{\frac{\varepsilon+1}{2}}} K_3 \frac{s}{s+g} \tanh(\beta l) \tag{2}$$

In Equations 1 and 2, K_1, K_2 and K_3 are proportionality constants which have to be characterized by simulation or measurement. Figs 2b and 2c respectively show the results of calculation and simulation for the propagation constant against frequency and the characteristic impedance of the SSPP transmission line against frequency when s=1mm, g=1mm and d=3mm.

From Equations 1 and 2, it can be observed that both *d* and the ratio *s/(s+g)* can be changed to change the characteristic impedance. The change in ratio *s/(s+g)* will not significantly affect the frequency characteristic of the SSPP transmission. The change in the slot depth will induce change in the propagation constant, thus the shifting the cutoff and resonant frequencies of the SSPP transmission line.

The base height of the metal pattern *b* in the printed circuit determines how much electromagnetic energy is converted into surface modes from the incoming electromagnetic energy from the input port. The electric field is always strongest along the center propagation axis of the waveguide. For the E-plane endfire antenna operates almost entirely on the surface modes, the base height of the metal pattern b should be approximately half the waveguide height.

The length of the SSPP transmission line should be one or three quarter wavelengths. In this work, all our designs use three quarter wavelengths as the length of the SSPP transmission line.



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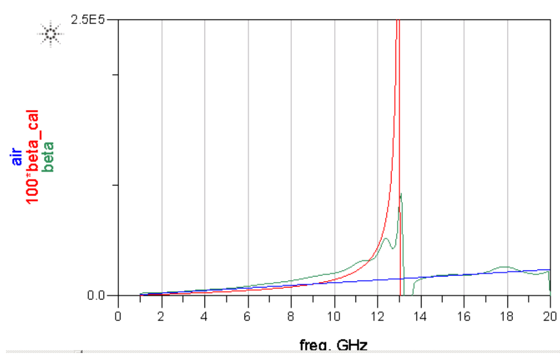

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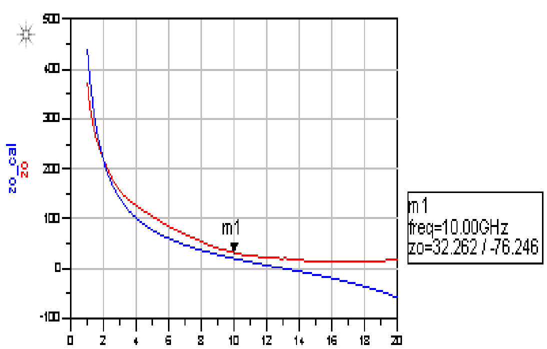


(c)

Figure 2. Details of E-plane printed circuit to be mounted in the rectangular waveguide. a) the side view; b) computed and simulated propagation constant as a function of frequency; and c) computed and simulated characteristic impedance of the SSPP line as a function of frequency.

Waveguide-to-SSPP transition: The waveguide-to-SSPP transition is tapered impedance transformer occupying one electrical wavelength, with the sole purpose of impedance matching between the waveguide and the SSPP transmission line. In this work, this transition is linearly tapered. It should be enclosed in the rectangular waveguide.

The electromagnetic energy propagating in the rectangular waveguide is in form of transverse electric modes (referred thereafter as TE modes) whilst the electromagnetic energy propagating in the SSPP transmission line is primarily in the form of surface modes. The characteristic impedance of a standard waveguide is approximately the characteristic impedance of free-space, which is 377 ohms. The characteristic impedance of an SSPP transmission line depends on the geometry of the corrugated metal patterns, and by our simulation, its value was found to be anywhere between 50 ohms and 200 ohms.

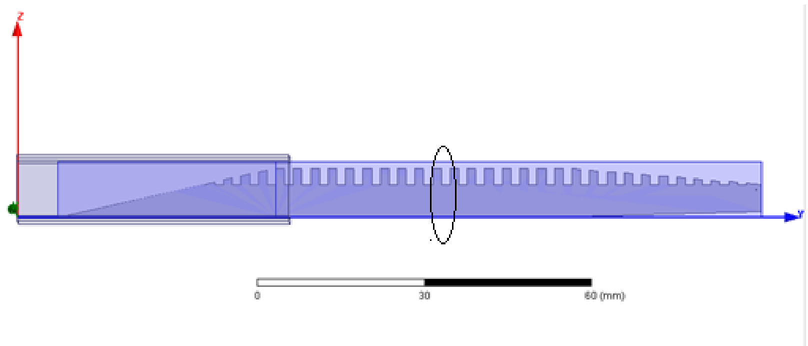
SSPP-to-air transition: The SSPP-to-air transition is tapered impedance transformer occupying one electrical wavelength, with the sole purpose of impedance matching between the SSPP transmission line and free space. In this work, this transition is linearly tapered. It should be completely exposed to air with the end pointing towards the direction of the endfire electromagnetic radiation.

The characteristic impedance of a standard waveguide is approximately the characteristic impedance of free-space, which is 377 ohms. The characteristic impedance of an SSPP transmission line depends on the geometry of the corrugated metal patterns, and by our simulation, its value was found to be anywhere between 50 ohms and 200 ohms.

The electromagnetic energy propagating in the rectangular waveguide is in form of transverse electric modes (referred thereafter as TE modes) whilst the electromagnetic energy propagating in the SSPP transmission line is primarily in the form of surface modes. The electromagnetic energy propagating in the air can exist in any mode. Inside a rectangular waveguide, where the fundamental mode of propagation is purely transverse electric, the electric field strength is expected to be maximum along the central propagation axis and be almost zero on the surface of the interior wall of the waveguide. On the other hand, the intensity of the surface wave along the SSPP transmission line is maximum at the corrugated edge if the operating frequency is below the cutoff frequency. In a preferred embodiment, the corrugated edge of the SSPP transmission line and the central propagation axis of the waveguide should be aligned with each other to further enhance the field strength of the forward travelling electromagnetic wave.

IV. E-plane SSPP endfire antenna with one corrugated edge

Fig. 3 shows the most basic form of the proposed antenna that operates at frequencies from 8GHz to 12 GHz. The performance of this version has not been properly optimized to unearth the potential of the proposed antenna. The parameters are: *s=1mm, g=1mm, b=6mm and* *d=3mm*. The SSPP-to-air transition is a linearly tapered, thus contributing some reflection as reflected by the simulated S-parameters shown in Fig. 3e. The simulated gains in this instance, as shown in Figs. 3b, 3c and 3d, are respectively 28 dB, 14 dB and 7 dB at frequencies 8 GHz, 9 GHz and 12 GHz.



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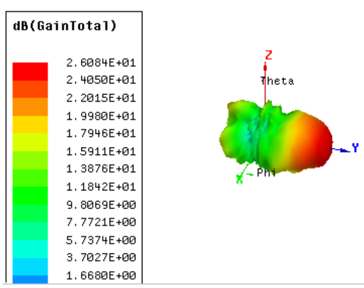
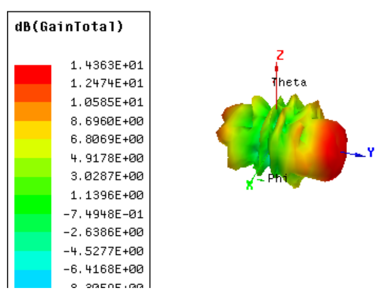
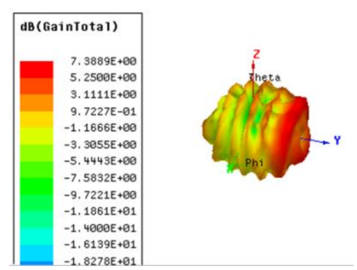
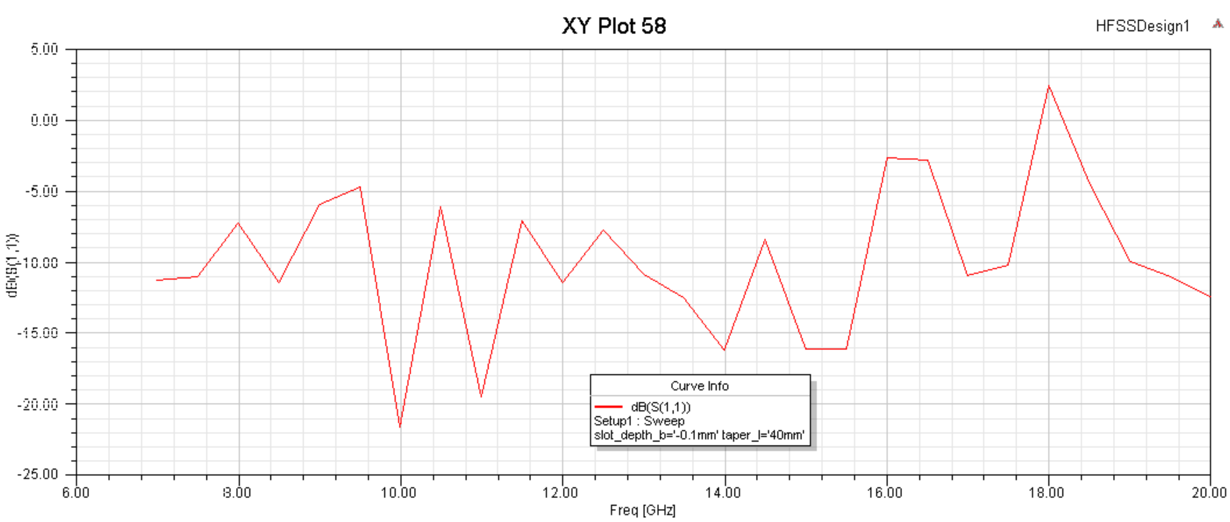






(b) (c) (d)



(e)

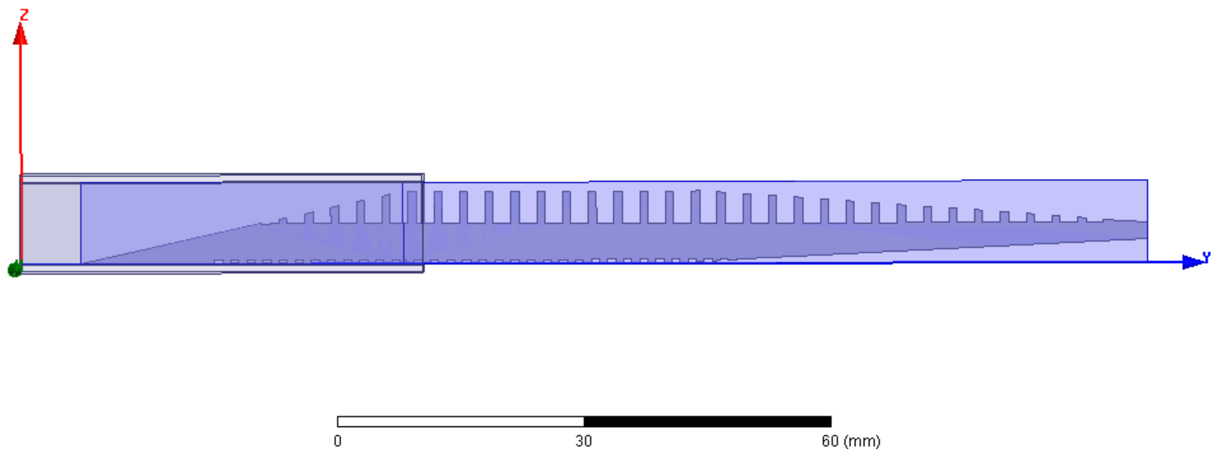
Figure 3. An E-Plane endfire antenna with linearly tapered SSPP-to-air transition. a) side view; b) Radiation Pattern at 8 GHz; c) Radiation Pattern at 9 GHz; d) Radiation Pattern at 10 GHz; and e) Simulated S-parameters.

V. E-plane antenna with geometry optimized for operation at 9GHz

The results of the electromagnetic simulation as shown in Fig. 3 has clearly shows that the E-plane endfire antennas in the previous example exhibit a gain which the average Vivaldi antenna cannot achieve. Whilst the presence of the E-plane printed circuit in the E-plane may be a cause of reflection, the result of our investigation further suggests that the slot depth *d* is the most influential parameter which determines the extent of reflection, and hence the S11 parameter.

In the example as shown in Fig. 4, the slot depth *d* was reduced to half of the height of the waveguide. On the other hand, the ratio *s/(s+g)* was further adjusted to maximize the gain. Other parameters of the present example were set in the same manner as those used in the example shown in Fig. 3 --- that is, the length of the SSPP transmission line is set at 3 quarter wavelengths and the length of the SSPP-to-air transition as well as the waveguide-to-SSPP were both set to one electrical wavelength.

Since the corrugated pattern is aligned with the center propagation axis, almost all of the incoming electromagnetic energy was converted into surface modes, which is the energy essential for generating an endfire radiation. As shown in Figs 4b, 4c, and 4d the simulated gain of the E-plane endfire antenna of the present example is at least 18 dB from 8 GHz to 10 GHz. Fig. 4f shows that the S11 parameters reached as low as -12dB from 8 GHz to 10 GHz, suggesting the reflection at this frequency range is no longer an issue. The apparent increase in gain can be further confirmed by the simulated S11 parameters.



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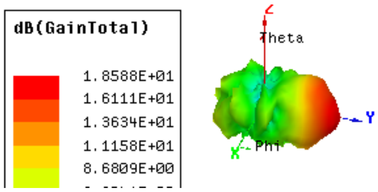

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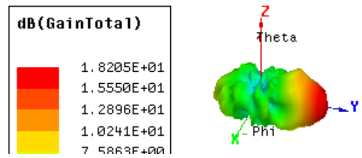

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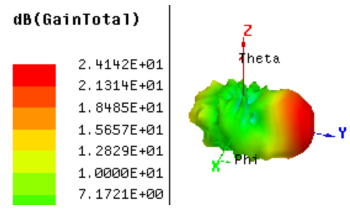

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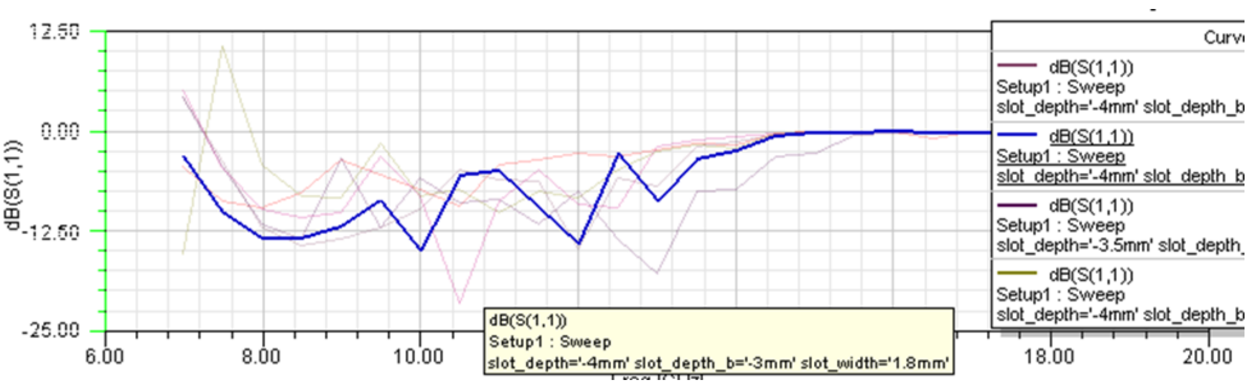
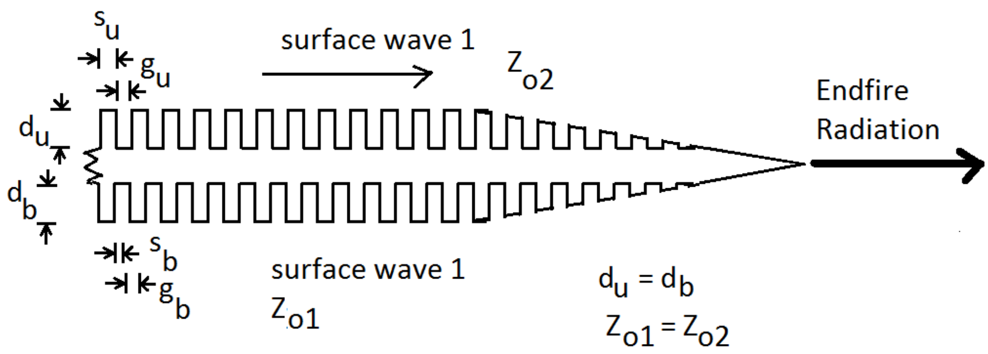


(e)

Figure 4. An E-Plane endfire antenna with geometry optimized for 9 GHz. a) side view; b) Radiation Pattern at 8 GHz; c) Radiation Pattern at 9 GHz; d) Radiation Pattern at 10 GHz; and e) Simulated S-parameters.

VI. E-plane antenna with frequency steerable endfire radiation

In this section, the concept of frequency dependent steering is presented. For the endfire radiation of an antenna to be frequency steerable, the SSPP transmission line must have both upper edge and bottom edge patterned with corrugated metal slot arrays. The slot depth of the corrugated upper edge must be different from that of the corrugated bottom edge. Fig. 5b illustrates the basic construction of an E-plane endfire capable of generating a frequency steerable endfire radiation.



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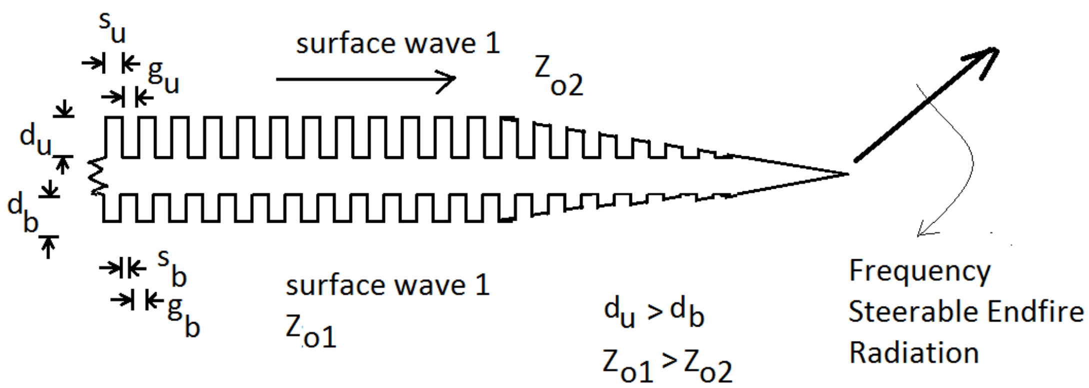

(b)

Figure 5. Mechanism of frequency dependent steering of endfire radiation. a) antenna no frequency steerable endfire radiation; b) antenna with frequency steerable endfire radiation.

As pointed out in Section III, the slot depth can induce change not only in the characteristic impedance of the SSPP transmission line but also in its frequency characteristic. When the slot depths for both upper and bottom edges are the same, the surface modes along the upper edge and the bottom edge will propagate in the same manner in the term of their frequency characteristics, and their supposition at the tip of the SSPP-to-air transition the antenna will result in an endfire radiation with no frequency steerable angle shift. However, if the slot depth of the upper edge is different from that of the lower edge, the surface mode 1 and surface mode 2 will behave differently at different frequencies. The superimposition of surface mode 1 and surface mode 2 will result in a noticeable frequency steerable endfire radiation.

Conclusions

We have presented an E-plane antenna permitting generation of a directional endfire radiation out of a spoof surface plasmon polariton, comprising

a) a rectangular waveguide, and
b) a printed circuit mounted on the center E-plane of the rectangular waveguide in (a).

The printed circuit mounted on the center E-plane of the rectangular waveguide contains

a) a tapered transition for converting a transverse electric modes to spoof surface plasmon polariton(s),

b) an SSPP transmission line of one-quarter or three-quarter wavelengths with the upper edge and/or the lower edge patterned with a corrugated pattern for propagation of spoof surface plasmon polariton(s), and

c) a tapered transition for impedance matching between the SSPP transmission line in (b) and free space.

For the endfire radiation of an antenna to be frequency steerable, the SSPP transmission line must have both upper edge and bottom edge patterned with corrugated metal slot arrays, and the slot depth of the corrugated upper edge must be different from that of the corrugated bottom edge.

Reference

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