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

Louis WY LIU

Department of Electronics Engineering, Southern University of Science and Technology, Shenzhen, China

Abstract

This presentation is related to an E-plane endfire antenna capable of generating an endfire electromagnetic radiation out of a spoof surface plasmon polariton (SSPP) with substantially enhanced gain. The core of the said antenna is a printed circuit vertically mounted in the center E-plane of a rectangular waveguide. The printed circuit is continuous metal pattern comprising three sections: a tapered section serving as a waveguide-to-SSPP transition, a corrugated transmission media for propagation of an SSPP and another tapered section for impedance matching between the corrugated transmission line and free space. The antenna accepts electromagnetic energy through the waveguide-to-SSPP transition in the input end of a waveguide, propagates the electromagnetic energy in the form of surface waves along the corrugated edge of the E-plane transmission line over 1-quarter or 3-quarter wavelengths and generates an endfire radiation through the SSPP-to-free-space transition in the other end of the same. The said antenna generates a near endfire radiation beam with a substantially enhanced gain, wherein the gain of the endfire radiation can be maximized by maintaining the slot depth to half of the waveguide height.

I. Background

The paper presents an antenna for generation of endfire radiations out of a spoof surface plasmon polariton transmission line mounted in 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 reason for such a low gain is because the whole metallic body of a Vivaldi antenna can radiate electromagnetic energy in 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 lost 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 inevitably encourages excitation of higher order modes. 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.

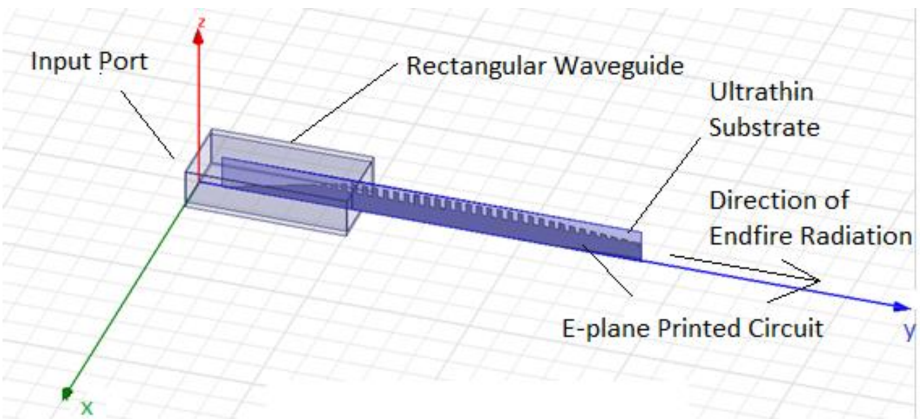
It is possible to cascade multiple endfire antennas into an endfire antenna array in a way to boost the antenna performance. Theoretically, such an arrangement allows the antenna gain to be substantially enhanced, say to exceed 10dBi, but this enhancement in gain comes at the expense of the area or volume. Most of the endfire antennas arrays published in open literature are extremely bulky, thus limiting their use in imaging applications.

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 the previous work, the original Spoof Surface Plasmon Polariton Antenna proposed did generate an endfire radiation but the radiation pattern also ended up with large side lobes in the neighborhood of the coplanar-to-SSPP transition due to the second order leaky modes. In the original design, the coplanar-to-SSPP transition itself, which has too many abrupt corners, inevitably encourages excitation of higher modes which potentially contributes to broadside radiations. In this work, however, these 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:

1) The printed circuit of the endfire antenna in the present presentation is mounted in the Center E-plane of the rectangular waveguide, where the second order modes are almost non-existent.
2) The metal wall of the rectangular waveguide blocks off all the broadside radiations.

II. Illustration 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. The E-plane printed circuit is vertically mounted in middle of the waveguide, which is also known as center E-plane [1-4]. The electric field strength from the incoming electromagnetic wave from the input port is always at the center 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 center 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.



III. Printed Circuit on the Proposed E-plane endfire antenna

The core of the E-plane endfire antenna in the present presentation is a printed circuit vertically mounted in the Center 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 transition from a rectangular waveguide to SSPP transmission line; 2) an SSPP transmission line of one or three quarter wavelengths; and 3) a taper impedance transformer which converts the characteristic impedance of the SSPP transmission line to the characteristic impedance of free space.

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. It 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 being less 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 combination determines the characteristic impedance of the SSPP transmission line as well as its propagation constant. Given that the slot wide is s, the slot depth is d 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). The slot depth d together with the characteristic impedance of this SSPP transmission line can be used to find its propagation delay or phase velocity.

The height of the metal pattern h in the printed circuit determines how much electromagnetic energy is converted into surface modes. Since the E-plane endfire antenna operates almost entirely on the surface modes, the height of the metal pattern h should be maximized to as close to the full height of the waveguide as possible.

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.

Waveguide-to-SSPP transition: 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 usually in the neighborhood 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, we found that its value could be anywhere between 50 ohms and 200 ohms. The transition from a rectangular waveguide to an SSPP transmission line is preferably a tapered. The length of the waveguide to SSPP transition is preferably one electrical wavelength. The whole waveguide-to-SSPP transition should be enclosed in the rectangular waveguide. In this work, a linearly tapered transition of one electrical wavelength was used.

SSPP-to-air transition: The electromagnetic energy propagating along the SSPP transmission line is in form of spoof surface plasmon polariton modes (which is also known as surface modes or SSPP modes) whilst the electromagnetic energy propagating in the air can be any mode. The transition from the SSPP transmission line to air is preferably a ridge completely exposed to air with the end pointing towards the direction of the endfire electromagnetic radiation. In this work, a linearly tapered ridge was used as an SSPP-to-air transition.

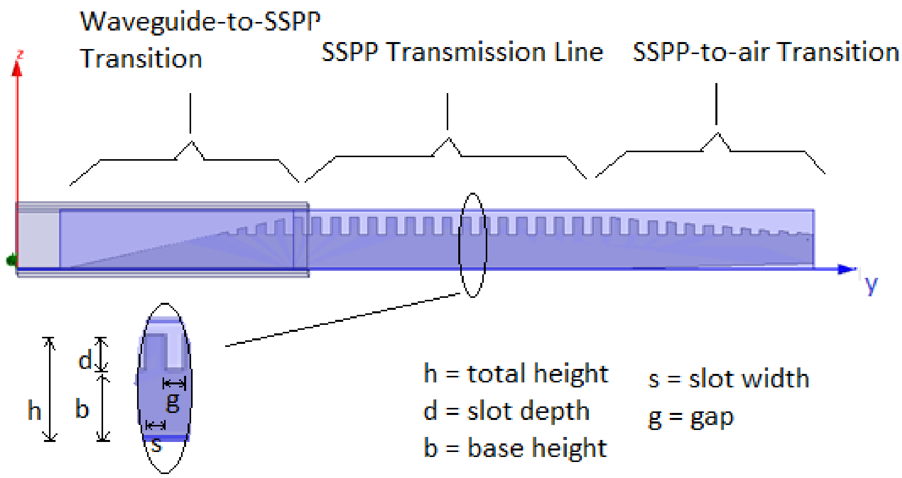


Figure 2. Example of E-plane printed circuit to be mounted in the rectangular waveguide

Electromagnetic energy primarily propagates inside a rectangular waveguide in transverse electric modes, with electric field strength being maximum along the central propagation axis and being almost zero on the surface of the interior wall of the waveguide. Along the central propagation axis, the field strength of the fundamental mode is maximum but the field strength of the second order mode is almost zero.

Since the intensity of the surface wave along the SSPP transmission line is maximum at the corrugated edge. On the other hand, the electric field strength at the central propagation axis of a waveguide is known to be highest. In a preferred embodiment, the surface wave along the SSPP transmission line and the central propagation axis of the waveguide are aligned to further enhance the field strength of the forward travelling electromagnetic wave.

<u>Example 1 – with a linearly tapered SSPP-to-air transition</u>

Fig. 3 shows an example design which is the most basic form of the proposed antenna that operates at frequencies from 8GHz to 12 GHz. The SSPP-to-air transition is a linearly tapered, thus contributing some reflection as reflected by the simulated S-parameters shown in Fig. 3f. The simulated gains in this instance are respectively 28 dB, 14 dB and 7 dB at frequencies 8 GHz, 9 GHz and 12 GHz.

<u>Example 2 – with a non-tapered SSPP-to-air transition</u>

Fig. 4 shows another example design which does not use any tapered SSPP-to-air transition. Without any tapered SSPP-to-air transition, the forwards wave propagate unhindered. Fig. 4f displays a noticeable improvement in the simulated S-parameters. However, the simulated gains in this instance are respectively 13 dB, 12 dB and 9 dB at frequencies 8 GHz, 9 GHz and 12 GHz. Compared to the previous example (i.e. example 1), the antenna gain in this example is constant but much lower.

Example 3 – E-plane antenna with geometry tailored for operation at 9GHz

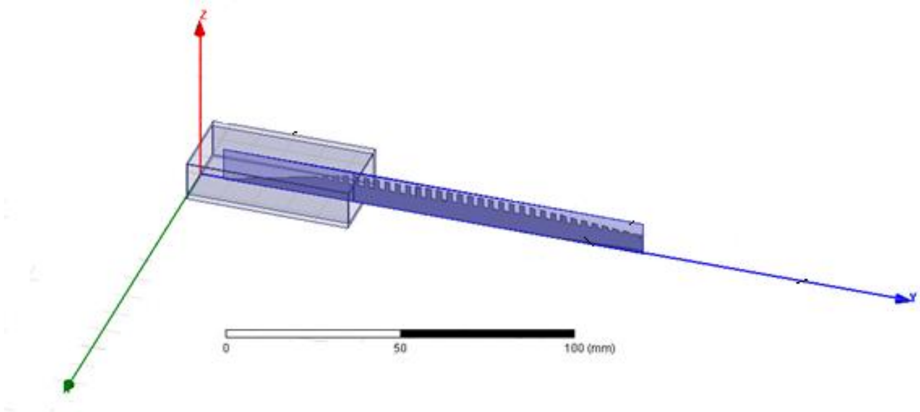
Whilst the electromagnetic simulation has clearly shows that the center E-plane endfire antennas in examples 1 and 2 exhibit a substantially high gain. In the present example, the S11 at the chosen operating frequencies (8GHz-10GHz) is lower than 10 dB. Whilst the presence of the E-plane printed circuit in the center 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 example 3, the slot depth d is reduced to half of the height of the waveguide. Assuming the waveguide together with the E-plane endfire antenna is placed horizontally as shown in Fig. 5b, the horizontal axis at half of the waveguide height is referred hereafter as the principle propagating axis. Since the corrugated pattern is aligned with the principle propagation axis, almost all of the incoming electromagnetic energy is converted into surface modes, which is the energy essential for generating an endfire radiation.

In example 3, the slot width s and the gap g between two neighboring slots can be further adjusted to maximize the gain.

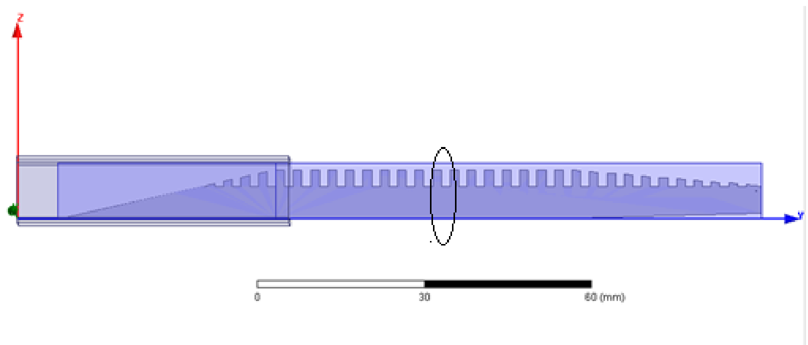
Apart from the slot depth d, the slot width s and the gap g, other parameters of the present example are preferably set in the same manner as those used in example 1 or 2. In exactly the same manner as in example 1 or 2, the length of the SSPP transmission line is set at 3 quarter wavelengths. The length of the SSPP-to-air is set at one wavelength.

The simulated gain of the E-plane endfire antenna of example 3 is at least 18 dB from 8 GHz to 10 GHz. Fig. 5f 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.

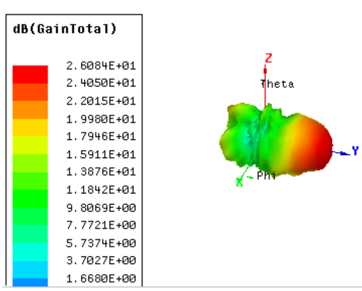


(a)

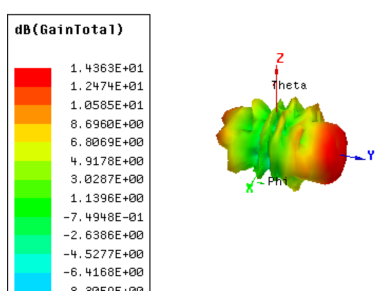
Figure 3. An E-Plane endfire antenna with linearly tapered SSPP-to-air transition. a) the isometric view; b) side view;



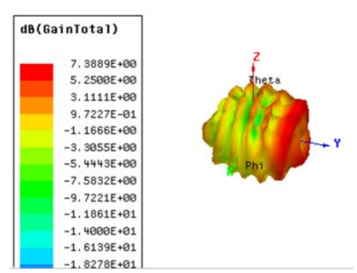
(b)



(c)



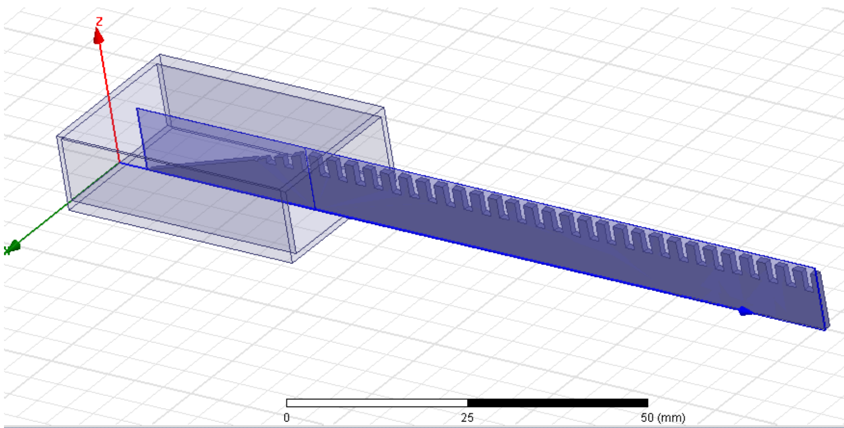
(d)



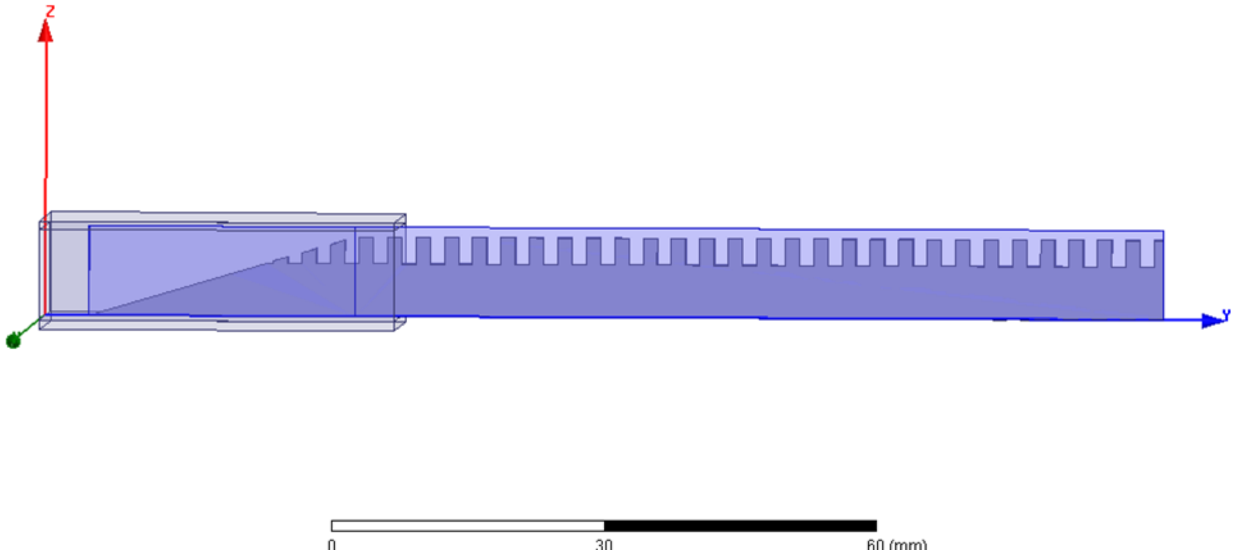
(e)

(f)

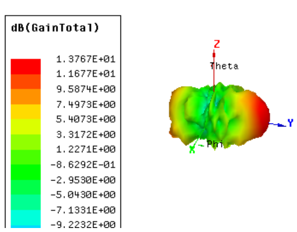
Figure 3. An E-Plane endfire antenna with linearly tapered SSPP-to-air transition. a) the isometric view; b) side view; c) Radiation Pattern at 8 GHz; d) Radiation Pattern at 9 GHz; e) Radiation Pattern at 10 GHz; and f) Simulated S-parameters.



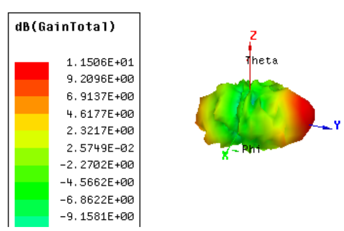
(a)


Z
Y
0
30
60 (mm)

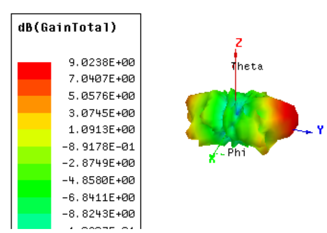
(b)


dB(GainTotal)
1.3767E+01
1.1677E+01
9.5874E+00
7.4973E+00
5.4073E+00
3.3172E+00
1.2271E+00
-8.6292E-01
-2.9530E+00
-5.0430E+00
-7.1331E+00
-9.2232E+00
Z
Theta
Y
X
Phi

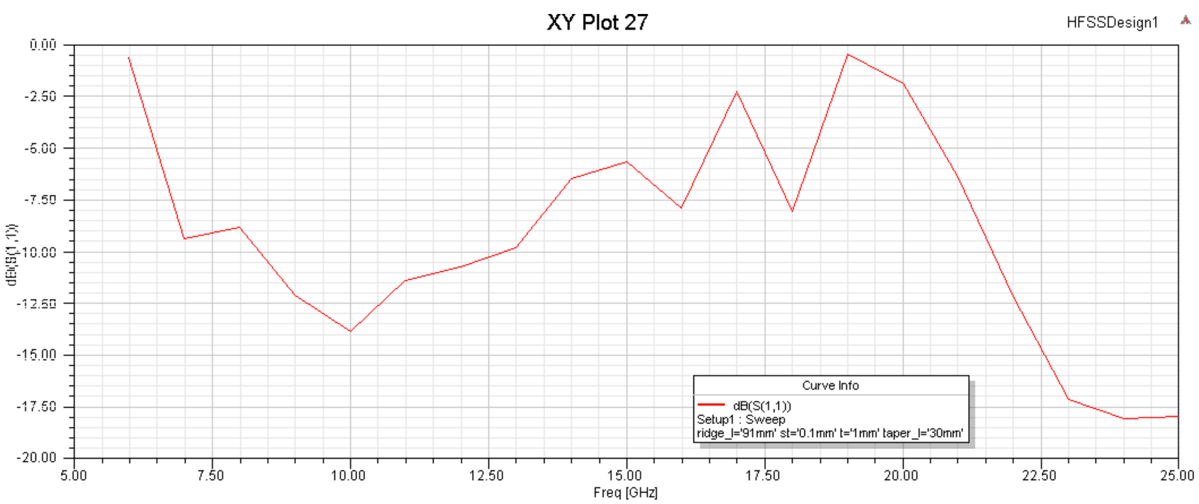
(c)


dB(GainTotal)
1.1506E+01
9.2096E+00
6.9137E+00
4.6177E+00
2.3217E+00
2.5749E-02
-2.2702E+00
-4.5662E+00
-6.8622E+00
-9.1581E+00
Z
Theta
Y
X
Phi

(d)

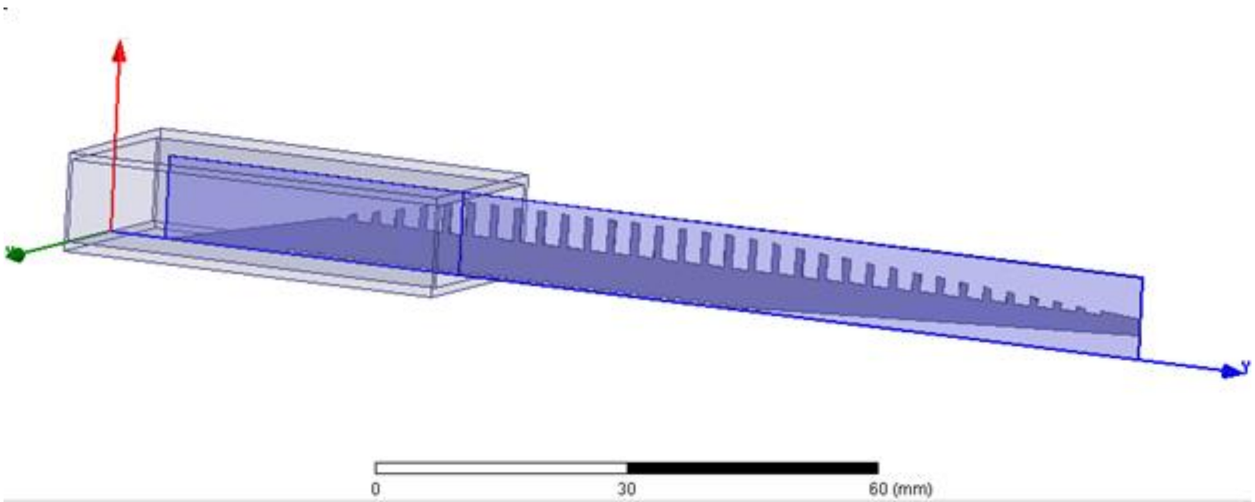

dB(GainTotal)
9.0238E+00
7.0407E+00
5.0576E+00
3.0745E+00
1.0913E+00
-8.9178E-01
-2.8749E+00
-4.8580E+00
-6.8411E+00
-8.8243E+00
Z
Theta
Y
X
Phi

(e)

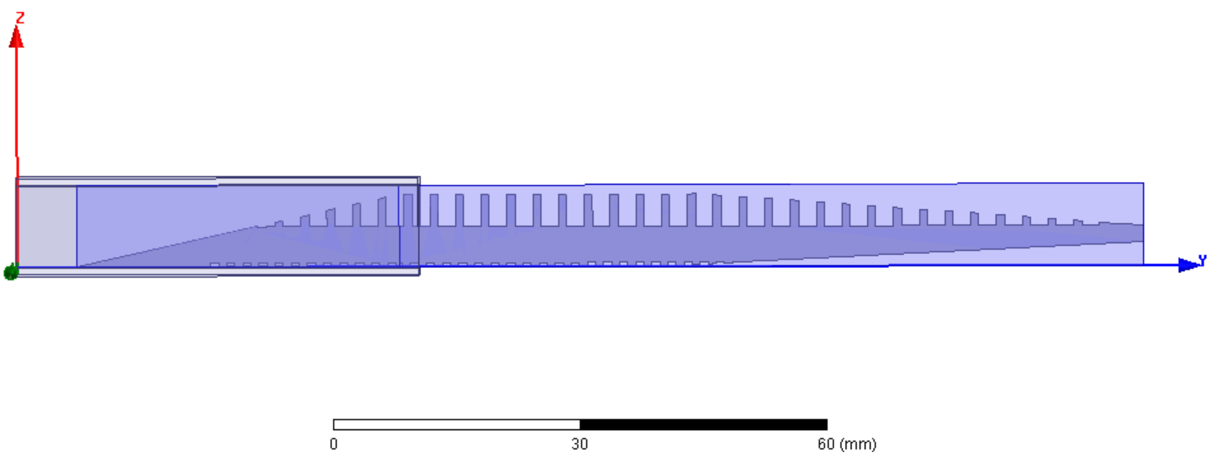

XY Plot 27
HFSSDesign1
0.00
-2.50
-5.00
-7.50
-10.00
-12.50
-15.00
-17.50
-20.00
dB(S(1,1))
5.00
7.50
10.00
12.50
15.00
17.50
20.00
22.50
25.00
Freq [GHz]
Curve Info
dB(S(1,1))
Setup1 : Sweep
ridge_l='91mm' st='0.1mm' t='1mm' taper_l='30mm'

(f)

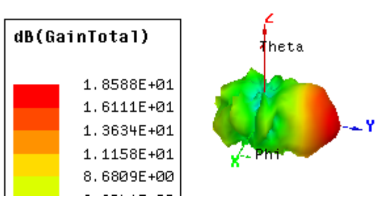
Figure 4. An E-Plane endfire antenna with non-tapered SSPP-to-air transition. a) the isometric view; b) side view; c) Radiation Pattern at 8 GHz; d) Radiation Pattern at 9 GHz; e) Radiation Pattern at 10 GHz; and f) Simulated S-parameters.

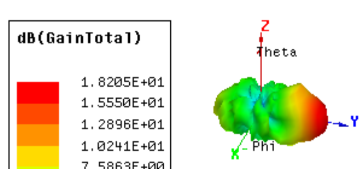


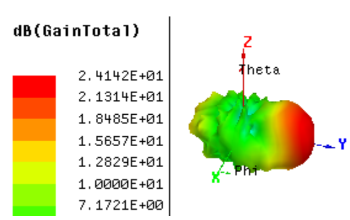
(a)



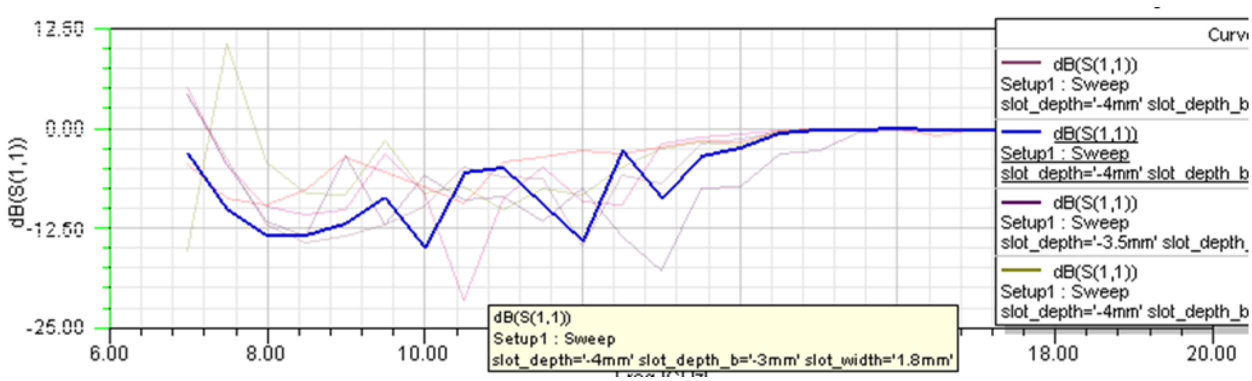
(b)







(c) (d) (e)



(f)

Figure 5. An E-Plane endfire antenna with geometry optimized for 9 GHz. a) the isometric view; b) side view; c) Radiation Pattern at 8 GHz; d) Radiation Pattern at 9 GHz; e) Radiation Pattern at 10 GHz; and f) Simulated S-parameters.

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.

Reference

1. W.Y.Liu, et al, "Membrane-Supported Copper Finline", IMS2001, May, 2001
2. W.Y.Liu, et al, "A Technique of Micromachining Suitable For Fabrication of Submillimeter Wave Components", Proc. SPIE 4088, pp 144-147, September, 2000.
3. W.Y.Liu, "Novel Technique of Thin Photoresist Micromachining for Submillimeter Wave Circuits", Proc. SPIE, Vol 4176-28, September 2000.
4. W.Y.Liu, et al, "A Simple but Novel Technique of Micromachining for Millimeter Wave and Submillimeter Wave Applications, IWMF'2000 Workshop, Oct. 9-10, 2000.
5. Abhishek Kandwal, Zhang Q, Louis WY Liu, et al, ”Low-Profile Spoof Surface Plasmon Polaritons Traveling-Wave Antenna for Near Endfire Radiation", IEEE Microwave and Wireless Components Letters, Vol. 17, November, 2017