Design Study of Electronically Steerable Half-width Microstrip Leaky Wave Antennas

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Abstract

A half-width microstrip leaky-wave antenna (HMLWA) having electronic beam steering capabilities is presented. Electronic beam scanning is demonstrated in X-, Ku- and Ka-bands through detailed design analysis and measurements. Two physical design approaches are studied; one requiring multi-layer processing and another requiring only a single layer metallization. In this paper, only the single layer design was implemented. Varactor diodes are edge coupled to the antenna element to achieve beam scanning as a function of the applied voltage at a fixed frequency. Beam scanning of 45-degrees for an 8 GHz design and 30-degrees for a 16 GHz antenna design are demonstrated. Details of design, fabrication and measurements are presented.

1. Introduction

Leaky wave antennas have been continuously studied over the last several decades and the principles of the antenna design are summarized in [1, 2]. As the name suggests, a leaky wave antenna is a waveguiding structure that lets power leak along its length. It provides broad range scanning and has high directivity. A variation of the classical microstrip leaky wave antenna is the Half-width Microstrip Leaky-Wave Antenna (HMLWA). It provides a simple and low-cost approach to achieving beam-scanning. Its feed circuit is simple to design. Similar to other leaky wave antennas, it is simple to fabricate, it has low profile and can be conformed to any curved surface. It holds significant potential for use in anti-collision for automobiles, thin-film RFID, communications and many military applications.

Fig. 1 shows the schematic diagram of a HMLWA. It consists of a half-width microstrip with one side connected to the ground plane using vias (electric wall) and the other edge left open through which the power radiates [3]. It is fed by a 50 Ω transmission line and is terminated with a 50 Ω load on the other end to minimize reflections (suppress backward waves). The length of the half-width microstrip acts as an effective line source antenna. It is designed such that most of the power has leaked away before reaching the other end. A narrow beam is produced in the scan-plane and a fan-beam on the cross-sectional dimension of the leaky wave antenna. The width of the half-width microstrip determines the frequency band of its operation. As a rule of thumb, the width of the microstrip line is taken to be equal to one quarter of the wavelength in the substrate medium onto which the antenna is fabricated upon.

Existing approaches are based on the use of frequency tuning to achieve beam scanning. Although beam scanning by frequency tuning makes the antenna design simple; but, beam scanning at a fixed frequency is desirable as it simplifies the design at the systems level and will find a wide range of applications. It is especially desirable where the frequency of operation is limited in bandwidth (e.g., communications). The radiation in a leaky wave antenna occurs approximately at the angle:

$$\theta = \sin^{-1}\left(\frac{\beta}{k_o}\right) \qquad (1)$$

Where θ is the radiation angle and k_o is the free space wavenumber, and β is the propagation constant. Reactive elements at the radiation edge can be used in order to control the radiation angle [4]. Recently it was shown that capacitors can be loaded on the edge to alter the radiation properties of the aperture of a HMLWA [5]. In this paper we build upon this work by implementing electronically tunable capacitive elements to achieve real-time beam scanning capability at fixed frequencies.

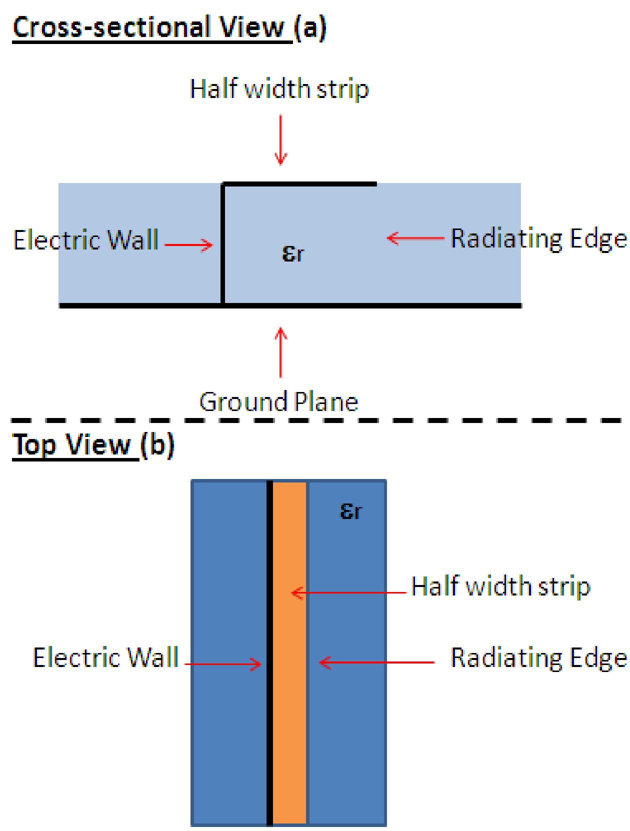

Figure 1. Basic HMLWA geometry

In order to integrate varactor diodes with the HMLWA, two physical design-layouts are presented. Designs are carried out for three different frequency ranges (X-, Ku- and Ka-band). Simulations are carried out using the FEM based High

Frequency Simulation Software (HFSS). One of the physical designs was fabricated for the X- and Ku- frequency bands and details of measured and simulation results are presented for these bands. Varactor diodes are interfaced allowing for continuous beam scanning at fixed frequencies. Only simulation results are presented for the other antenna designs.

1. Unloaded Antenna Simulation Results and Fabrication

To demonstrate a HMLWA at high frequencies, an unloaded Ku-band antenna was designed, fabricated and tested. The antenna was designed using the dielectric properties of a 0.508 mm Rogers RT/Duroid 5880 substrate (ε_r = 2.2, tan-δ = 0.001). The half width of the antenna was designed to be 2.9 mm. The length of the half width microstrip leaky wave antenna was 125 mm. The antenna was fed using an SMA connecter followed by a 50 Ω microstrip line, and terminated with a 50 Ω microstrip line in series with a 50 Ω SMA load. Fig 2 shows the simulated return loss of the half width microstrip leaky wave antenna.

Fig 3 shows the fabricated antenna. The electric wall was fabricated by drilling 0.2mm diameter holes along the edge of the half width strip and then stitching a copper wire through the holes followed by applying solder on the top and bottom part of the stitch.

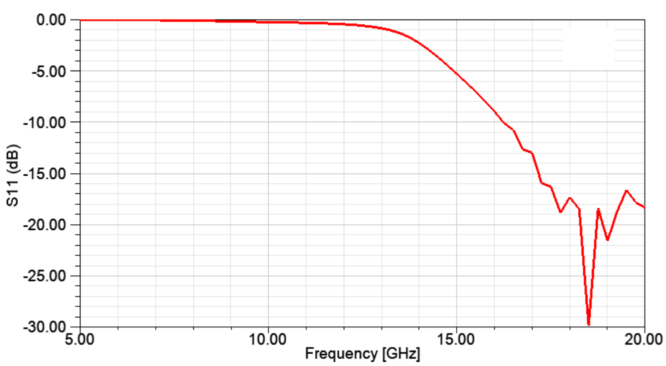

Figure 2. Simulated return loss (S11) of the Ku band HMLWA.

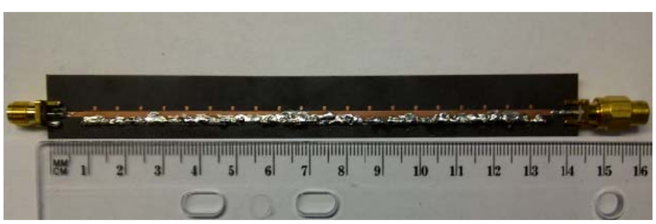

Figure 3. Ku band fabricated unloaded HMLWA.

2. Frequency Based Beam Steering of the Unloaded Antenna

Main Beam steering of the HMLWA pattern can be achieved using frequency tuning. This is done by changing the frequency of the wave feeding the antenna within the defined band. This was shown in the case of the Ku band half width microstrip leaky wave antenna through simulation and measurement. Fig. 4 shows the frequency based beam steering obtained from simulation and measurement for a Ku-band design. The result shows that beam scanning can be achieved by frequency tuning. The feasibility of tuning the main beam of a half width microstrip leaky wave antenna at a fixed frequency was investigated for such an antenna by employing varactor diodes as discussed ahead.

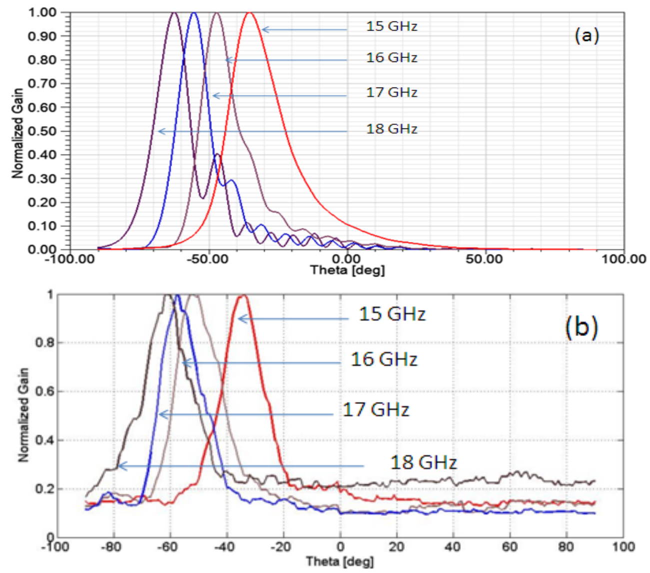

Figure 4. Simulated and measured main beam locations as a result of frequency based beam steering of the Ku band HMLWA.

Half Width Microstrip Leaky Wave Antenna Varactor Based Single Frequency Beam Steering

Detailed study in ref. [5] showed that the radiating edge can be loaded with small capacitors to achieve beam scanning with varying capacitance values. Simply stated, the paper suggests that by effectively modifying the width of the half width microstrip, the main beam can be steered at a single frequency. This was demonstrated using fixed value capacitors. In this paper, varactor diodes instead of fixed value capacitors are implemented. The antenna structure was modified to accommodate the varactor diodes. Varactor diodes are components which have the ability to vary their junction capacitance when they are reverse biased. The key requirements of the varactor diodes integration include: 1) high cut-off frequency (beyond the frequency of operation), 2) large tuning range of capacitance value to achieve wide tuning range; (3) compact size to minimize perturbation of the radiation pattern, and (4) ease of DC biasing.

1. Design Modifications for Tunable Capacitor Accommodation

Feasibility simulations were carried out in order to test whether capacitive tuning can achieve fixed frequency beam steering. Balancing fabrication and design requirements, two different antennas were designed having different physical layouts. They differ by the way the varactor diodes are integrated with the antenna element. Given the basic geometry of a half width microstrip leaky wave antenna, a direct edge mounting will lead to a DC short. To avoid DC shorting, capacitive coupling is required while achieving desired impedance at the frequency of operation.

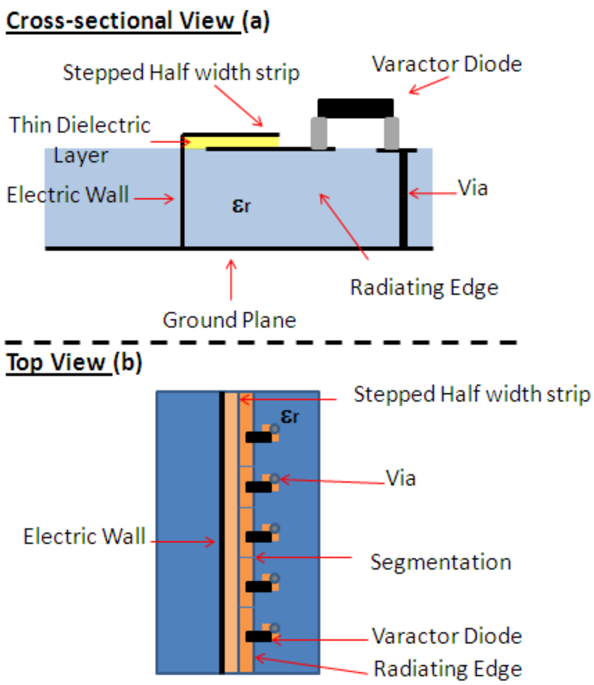

Figure 5. HMLWA Modified Geometry - Design 1.

Two different designs modified from the basic HMLWA design are investigated here. In the first approach, the half width strip of the LWA was substituted with two strips separated from each other by a very thin dielectric. One of these strips would be DC shorted to the ground and the other will be capacitively coupled (low RF impedance) with the antenna. The tunable element is then connected between the capacitively coupled strip and the ground plane, Fig 5.

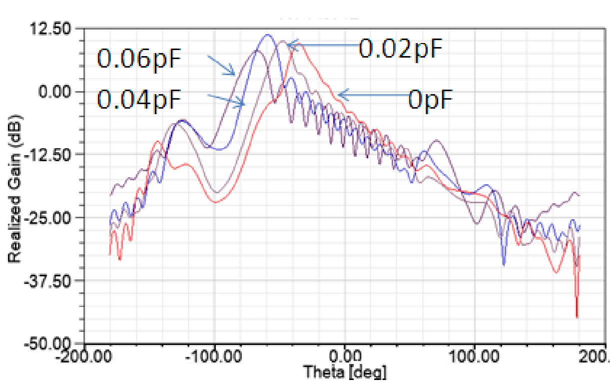

Figure 6. Simulated fixed frequency beam steering using capacitive tuning – Design 1.

This design was tested through simulation of a Ka-band antenna. The substrate employed in the simulations was LCP (ε_r = 3.15, tan-δ = 0.003) [6]. The substrate thickness was 0.165 mm. The thickness of the capacitance dielectric was 10 µm LCP. The microstrip line connected to the electric wall was designed to be 0.8 mm wide and 71 mm long. The microstrip line that was not connected to the electric wall was designed to be 1.59 mm wide and 71 mm long. The separation between this microstrip line and the electric wall was chosen to be 100 µm. Also, the microstrip line that was not connected to the electric wall was segmented into 20 equal segments with 100 µm separation between the pads. This allows for independent tuning of the varactor diodes. In the simulation, the capacitors were setup to be surface mounted touching the microstrip on one end and a via on the other end connecting that end to the ground plane. For this simulation, all varactor diodes were tuned simultaneously between 0 - 0.06 pF. Increasing the capacitance on the free edge of the microstrip segments is effectively equivalent to increasing the width of the microstrip. An increase in the width of the microstrip shifts the operational frequency band downwards. Hence, in order to achieve the largest beam steering dynamic range, the loaded antenna must be operated at a frequency located at the lower end of the band of operation of the unloaded antenna. A frequency of operation of 26.5 GHz was chosen for the antenna design. The simulated radiation pattern of the antenna was acquired for several different capacitance values loading the edge of the antenna. The steering width of the antenna approaches a range of 32-degrees (difference between the main beam angle with 0pF and 0.06pF), see Fig 6.

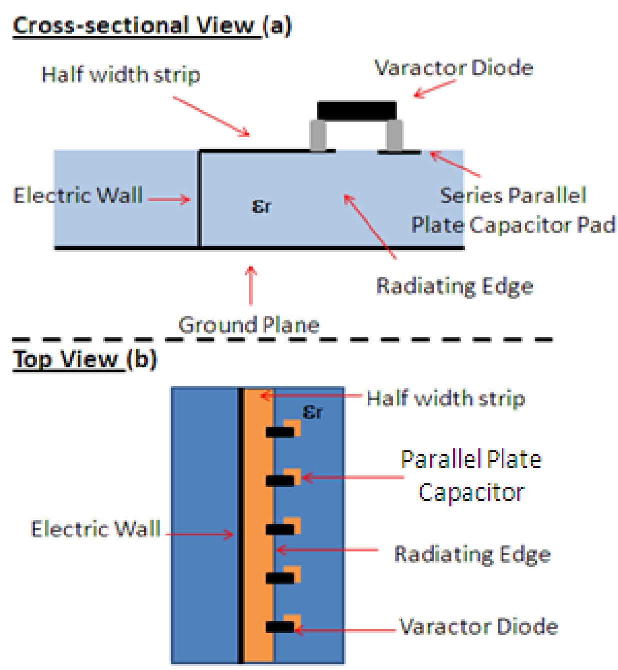

Figure 7. HMLWA Modified Geometry - Design 2.

In the second modified design, Fig 7, periodically placed microstrip pads were added along the length of the half width microstrip. The varactor diodes were mounted on one end to the half width strip and on the other end to the periodically placed pads at the same metallization layer as the antenna element. The pads were not shorted to the ground hence serving a dual purpose. First, they prevented the shorting of the leads of the varactor diodes. Second, they acted as parallel plate capacitors in series with the varactor diodes. This is advantageous as this approach allows flexibility in the capacitance values of varactor diodes which can be compensated by the series parallel plate capacitor. Furthermore, this approach is also simple to fabricate as it requires single layer processing. By having independent pads for each varactor diodes can be individually tuned to achieve desired beam scanning.

The design was tested through the simulation of an X-band leaky wave antenna using variable capacitances at a fixed frequency of 8 GHz. The antenna was designed on a 1.57 mm thick RT/Duroid 5880 substrate (ε_r = 2.2, tan-δ = 0.001). The half width of the antenna was 5.07mm and its length excluding the feed and termination 50 Ω lines was 125mm. The antenna was fed using an SMA connector followed by a 12.5mm 50 Ω line and terminated with a similar structure having a 50 Ω line followed by a 50 Ω SMA termination. The periodic pads were designed to occupy 4.85 mm^2 with a 100 µm gap between every two consecutive pads. Fig. 8 shows a sketch of the periodic pads (or parallel plate capacitor) details. The gap between the capacitive pads and the main half width strip of the leaky wave antenna was chosen to be 150 µm. The capacitance was varied between 0 pF and 0.75 pF. The dynamic main beam tuning achieved in this simulation was around 42-degrees. Fig. 9 shows the beam steering achieved using this design approach by utilizing capacitive tuning.

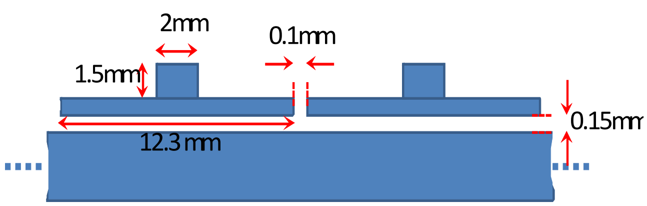

Figure 8. Periodic Pads' Dimensions (top view)

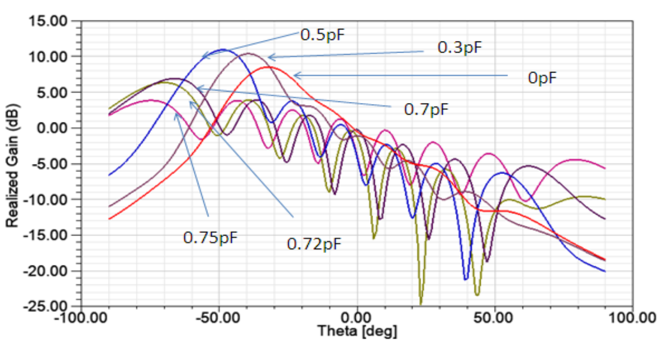

Figure 9. Simulated fixed frequency beam steering using capacitive tuning – Design 2.

2. Measured Loaded Antenna Beam Steering Results

Due to varactor diode junction capacitance commercial availability limitations and the ease of fabrication, the second modified design approach was used because of the flexibility it offers in that sense. Two similar designs were fabricated differing mainly by frequency of operation. The frequencies are 8.8 GHz (X band) and 16 GHz (Ku band). The varactor diode acquired and used for fabricating the antennas is the SMV2019-SC79F from Skyworks Solutions. This diode has a capacitance tuning capability ranging from 0.3pF at highest reverse voltage biasing up to 2.2pF at lowest reverse voltage biasing. The bare die of this diode is rated capable of being used at frequencies above 40 GHz. However, in packaged form, the cutoff frequency is reduced (to 30 GHz) due to parasitics associated with packaging.

Fig. 10 shows the picture of an X-band antenna with surface mounted varactor diodes. The dimensions of this antenna are the same as the dimensions of the simulated X-band antenna presented earlier. The varactor diodes were connected in parallel for DC biasing using a thin wire. This connection was not optimized for this design. Fig 11 shows the measured beam steering of this antenna as a function of bias voltage. With decrease in voltage, or increase in capacitance value, the main beam angle steers away from 0-degrees. The beam tuning covers a range of about 45-degrees. The highest bias voltage (20 V) corresponds to the lowest capacitance (0.3 pF) while the lowest bias voltage (0V) corresponds to the highest capacitance possible on the varactor diode (2.2 pF). While the steering capability has been shown in simulation and measurements, the steering performances differ in the range of angles they cover. This difference is attributed to the wires used in biasing the varactor diodes. These wires introduce unaccounted series inductance and also may be leading to scattering at the radiating edge.

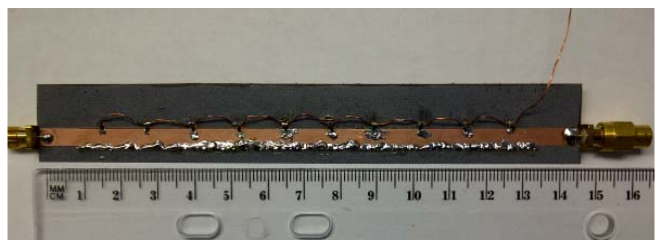

Figure 10. X-band fabricated HMLWA mounted with 10 varactor diodes.

The Ku-band antenna was made on the same dielectric substrate with a thickness of 0.507 mm. The half width of the antenna was 2.53 mm and its length excluding the feed and termination 50 Ω lines was 62.5 mm. The antenna was fed using an SMA feed followed by a 12.5 mm 50 Ω line and terminated with a similar 50 Ω line followed by a 50 Ω SMA termination. The periodic pads were designed to occupy 0.8mm^2 (0.8 mm X 1 mm) with 5.45 mm gap between every two consecutive pads. The gap between the capacitive pads and the main half width strip of the leaky wave antenna was chosen to be 200 µm. Fig 12 shows the Ku-band fabricated antenna, and Fig 13 shows the Ku-band antenna measured beam steering results. Again, similar to the X-band antenna, beam steering capability was shown with the Ku-band antenna as a function of varactor diode bias voltage. The results show a dynamic tuning range of about 30-degrees. As the voltage increases (capacitance decreases) the beam shifts towards 0-degrees. The performance of the antenna can be further improved by optimizing the DC bias circuitry and the integration of varactor diodes.

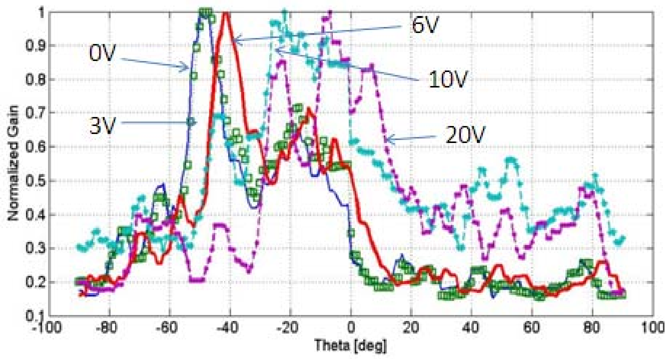

Figure 11. X-band antenna measured beam steering results as a function of the reverse bias voltage of the varactor diode

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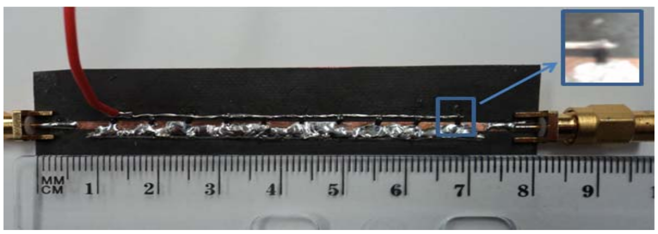

Figure 12. Ku-band fabricated HMLWA loaded with varactor diodes in addition to the biasing circuitry.

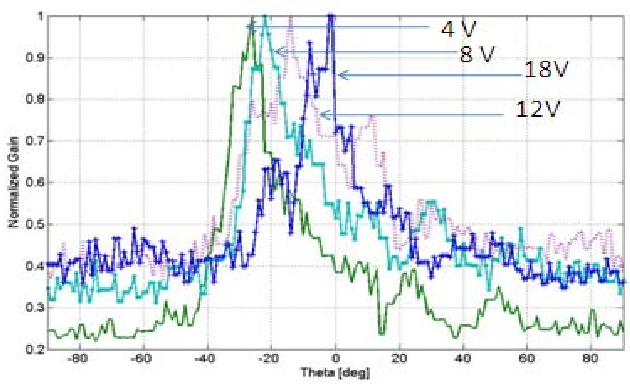

Figure 13. Ku-band antenna measured beam steering results as a function of the reverse bias voltage of the varactor diode.

3. Embedded Variable Capacitors Antenna Beam Steering Simulation Results

The above results clearly show that varactor diodes can be incorporated to achieve beam scanning at a fixed frequency. In order to further improve processing and manufacturability, and to reduce parasitic associated with packaging, an embedded device approach is analyzed. In this approach, the active devices (varactor diodes here) are embedded as an integral part of the antenna element within the dielectric substrate. Through this approach, use of wire bonding and soldering can be avoided. In order to quantify this approach, detailed design and simulation were carried out by considering details of the physical layout of the embedded design. The antenna element design is similar to other designs presented in this paper.

As an example, a Ka-band antenna was designed using the embedded physical layout approach. The substrate employed in the simulations was LCP having a thickness of 0.165 mm. A 10 μm layer of LCP was used to achieve strong capacitive coupling leading to lower-impedance. The microstrip line connected to the electric wall was designed to be 0.8 mm wide and 71 mm long. The microstrip line that was not connected to the electric wall (grounded vias) was designed to be 1.59 mm wide and 71mm long. The separation between this microstrip line and the electric wall was chosen to be 100 μm. Also, the microstrip line that was not connected to the electric wall was diced into 20 equal segments with 100 μm separation between the pads. This allows for independent tuning of the varactor diodes. At each segment, a 20 μm deep via connects the varactor diode to the top metal. The varactor dimensions are 100 μm thick, 250 μm wide and 600 μm long. The other side of the varactor diode is connected to the ground using a 45 μm long via. DC interconnects for the varactor diodes were also included in the simulations. The DC interconnect is made at the second level metallization, and the probe pad are made on non-radiating side of the antenna. This interconnect crosses the metal wall. The interconnect width is 250 μm, while its length is 600 μm from end to end. The hole in the electric wall (for all interconnects) is 70 μm tall and 300 μm wide. Fig 14 shows a simplified sketch of the final design for the HMLWA simulated with embedded tuning elements.

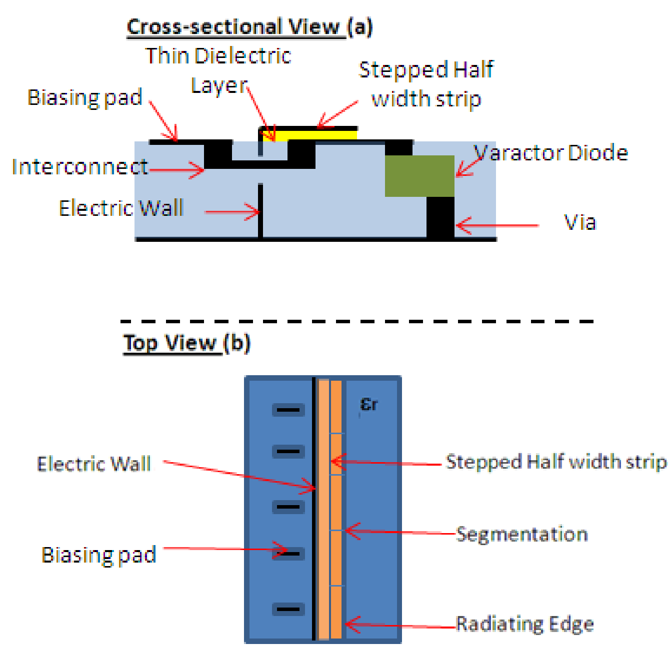

Figure 14. HMLWA with embedded tuning elements design.

In the simulation, the varactor diodes were tuned simultaneously between 0 pF and 0.045 pF. Increasing the capacitance on the free edge of the microstrip segments shifted the main beam location away from 0-degrees. The antenna main beam location as a function of capacitance was obtained and is shown in Fig 15. For this capacitance tuning range, 40-degrees steering range is achieved. This simulation shows clearly that embedding the tunable elements can be implemented in high frequency designs. In addition, this design allows an efficient approach to implement DC bias circuitry for the varactor diodes that does not perturb the radiated field.

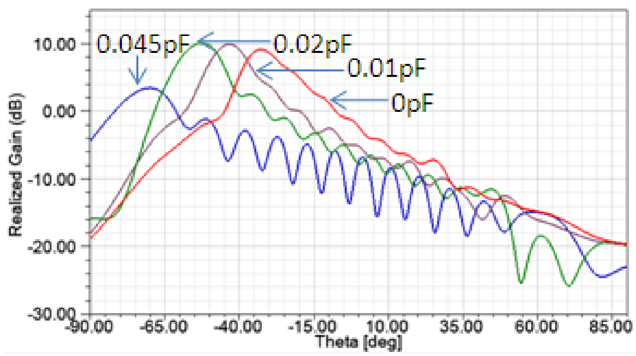

Figure 15. Simulated fixed frequency beam steering using capacitive tuning – embedded tuning elements design.

Conclusions

In this manuscript, a study of half-width microstrip leaky wave antennas was presented. As an example, a basic Ku-band unloaded microstrip leaky wave antenna was designed, simulated and tested. The ability to accomplish frequency based beam steering was shown using this antenna. Through simulations, two approaches for the integration of varactor diodes with the antenna elements have been demonstrated. One of these approaches, single layer metallization, was used to fabricate electronically steerable X-band and Ku-band antenna designs. Beam scanning of 45-degrees for an 8 GHz design and 30-degrees for a 16 GHz antenna design are demonstrated. To our knowledge, electrical beam scanning using half-width microstrip antenna presented here for the first time at these high frequencies. As an alternate to surface mounting of varactor diodes, an approach to fabrication of antenna elements with embedded diodes for Ka-band and higher frequencies has been demonstrated through simulations. Embedding of diodes reduces parasitics and thus allows for high frequency operation. Also, it is possible to independently control the varactor diodes to allow further flexibility in beam steering. This will be further investigated.

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