A Reconfigurable Leaky Wave Antenna

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Abstract— **A design of a reconfigurable leaky wave antenna in the form of an 1D array of mushroom cells working at around frequency 3.25 GHz is presented. The reconfigurability is obtained by controlling capacitances of varactors connected between particular cells. The antenna array shows a control of the direction of the main lobe of the radiation pattern within a given span of elevation angles, which is achieved by setting the DC varactor bias. Both simulations and measurements verify the effectiveness of the presented antenna design. Simulations show the variation of the main lobe radiation pattern within approximately 45° at 3.25 GHz when changing the applied DC voltage between 15 and 29 V. Unfortunately, the fabricated antenna specimen reaches a narrower span of elevation angles. The overall behavior is, however, similar as predicted by simulation. The designed antenna has a simple structure that can be cheaply fabricated by PCB process.**

Keywords— ***Reconfigurable antenna, leaky wave antenna, mushroom cell, varactor.***

I. Introduction

Leaky wave antennas (LWAs) can be structured as arrays of individual cells [1], which can take, e.g., the form of conducting patches forming mushroom cells [2]. They can be designed to work as composite right/left-handed (CRLH) periodic structures [3–6]. The radiation patterns of these antennas can be controlled by changing the capacitances of properly connected varactors. The electronic control of the LWA beam steering is in fact an old story. The probably first paper dealing with this problem was [7]. The authors showed the beam scanned from -49° up to 50° at 3.33 GHz. Several works have appeared hereafter (see, e.g. [8-10]) all based on similar ideas of using varactors.

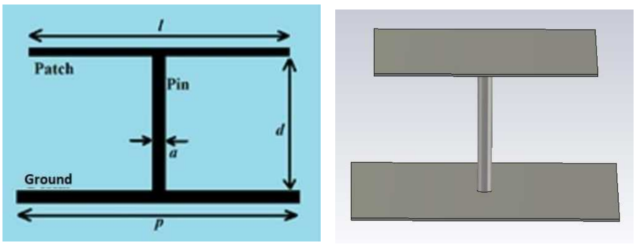
The ultimate goal of the research reported in this paper is to design and implement a 1D antenna array which is fed at a single point but possesses freely steerable radiation characteristics. The main idea behind the proposed concept is to utilize tightly coupled reconfigurable array of elements. The tight coupling is necessary for feeding the array at a single element, with the coupling being responsible for supplying energy to the other array elements.

There are several ways to provide reconfigurability for LWAs. The aim is to steer the main beam of the radiation pattern not by changing the frequency as in standard LWAs but by the external means of DC voltage. Liquid crystals have been used in a substrate integrated waveguide transmission line by the termination of central blind vias [11], achieving a beam steering of 30° at 52 GHz, or as a material changing the substrate permittivity [12], obtaining a beam steering of 24° at a frequency around 30 GHz. Huygens' metasurface in terms of cascaded tunable impedance layers has been controlled by varactors connected across these layers in loop unit cells [13], where an LWA showing a beam scanning between -30° and 30° at 5 GHz was presented. Piezoelectric actuators have been used to change the parameters of the substrate to tune the antenna behavior [14], showing a beam scanning of 30° at 37 GHz and 18° at 280 GHz. An LWA designed by the authors of [15] was based on coplanar waveguide (CPW) with slots crossing the central CPW strip bridged by MEMS and showed an extreme scanning ability of 126°, from -73° (backward wave) up to 53° (forward wave) at 77 GHz. A holographic metasurface has been used by authors of [16] showing the beam steered between 32° and 65° at 3.2 GHz (no experiment shown in [16]).

This paper uses the mushroom cell to design the required antenna array. Varactors are then properly connected to the structure to allow their feeding by DC voltage. Simulation results are verified by experiments, proving the effectiveness of the design. When changing the DC feeding voltage between 15 and 29 V, the designed LWA shows a change of the main lobe of the radiation pattern within 45° at 3.25 GHz. This occurs in the forward direction, i.e., in the right-hand (RH) mode. Measurements of the constructed antenna specimen show a narrower span of the elevation angles at the selected DC voltages equal to 20°.

The paper introduces a modification of the standard LWA composed of mushroom cells that will be presented in [17]. The LWA array is modified by properly inserted varactors that cross the slots between cells patches. The array is reshaped to allow connecting DC voltage fed varactors that are in fact connected in parallel, enabling the use of only one DC voltage source. The structure was analyzed in CST Microwave Studio (CST MWS) [18].

II. 2. Design of a Varactor-Controlled Leaky Wave Antenna, Experiment



(a) (b)

Fig. 1. Mushroom cell structure. (a) A sketch with dimensions; (b) a CST MWS model of one cell, not showing the dielectric substrate.

The mushroom cell [2] shown in Fig. 1 has been selected to serve as a building block of the LWA designed as a 1D periodic array. Referring to Fig. 1, the ground area is 19 mm

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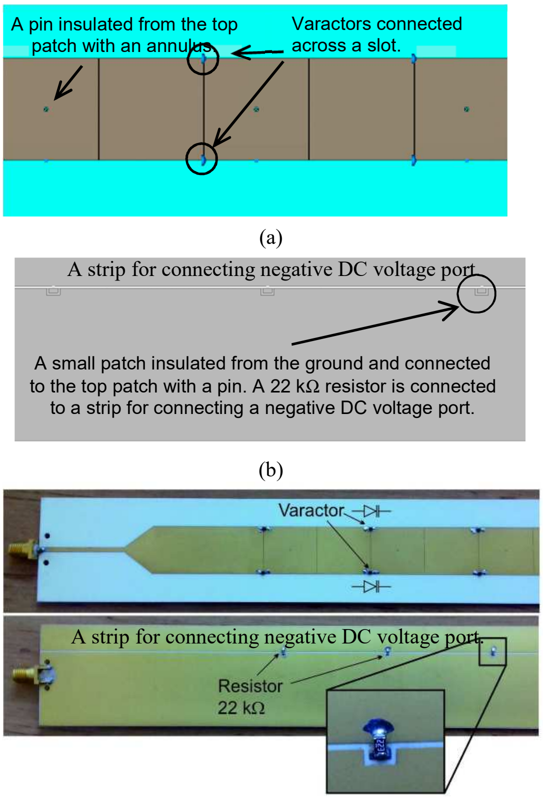
in length and 17 mm in width, the pin height (substrate thickness) is d = 0.762 mm, substrate permittivity is 3.48, and the pin diameter is a = 0.2 mm. The metallization thickness is 0.017 mm.

The originally presented LWA [17] has been modified into an array with varactor diodes controlling the shape of the array radiation pattern. The basic task is to incorporate varactors into the structure with corresponding serially connected resistors and to connect one DC voltage source. The simple antenna operation needs to use only one voltage source, so that the varactors must be connected in parallel. The reshaped CST MWS model of the antenna array, including varactors, is shown in Fig. 2.



(c)

Fig. 2. A detail of the CST MWS model of the antenna array with included varactors. (a) Top view, (b) bottom view, (c) a detail of the fabricated antenna specimen from top and bottom.

Two neighboring cells are connected by two varactors bridging the slot between them. The top patch of the first one is insulated from the pin with an etched annulus, as seen in Fig. 2a, to protect the DC voltage from a short circuit. A 22 kΩ resistor is connected in series with the varactor via a pin connecting the top patch of the second cell with a small patch insulated from the ground (Fig. 2b). A negative DC source port is connected to a conducting strip at the bottom surface of the substrate. In this way, all varactors are connected in parallel, and only one DC source is applied. The array uses BB837 varactors by Infineon [19]. These varactors can operate with a DC voltage between 0 and 30 V with a corresponding change of capacitance from 6.6 to 0.5 pF.

The antenna is in this new modification composed as the array of modified cells shown in Fig. 3. These cells have been used to design the reconfigurable antenna. Resonant frequencies of these cells determined by the Eigen mode solver of the CST Microwave Studio [18] define the onset of the antenna array radiation. The dependence of this onset on the slot width located between particular patches is plotted in Fig. 4. For frequency 3.25 GHz the slot width is 0.1 mm. By using these slots we have obtained radiation of the antenna controlled by value of capacitances of used varactors as shown by simulations in Fig. 8.

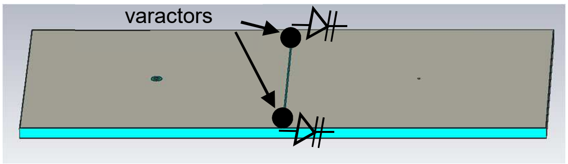


Fig. 3. A modified antenna cell.

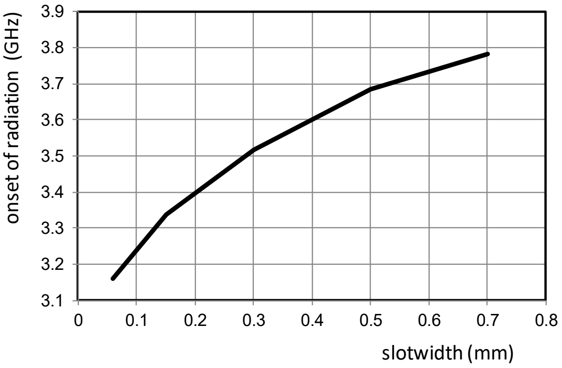


Fig. 4. An onset of the radiation of the antenna array depending on the width of slots located between

Fig. 5 compares sets of values of the scattering parameter S_{11} as calculated by CST MWS (solid lines) and as measured (dashed lines), plotted for selected values of varactor capacitances and selected voltages. Considering roughly the relation between the voltage and the corresponding varactor capacitance [19], the match of data presented in Fig. 3 is good. Following the match to a 50 Ω microstrip line, the array is applicable in dependence on the applied DC voltage determining the value of the varactor capacitances at frequency bands around 3.25, from 4.6 up to 4.9, and from 6 up to 6.2 GHz. As explained later, only band around 3.25 GHz has been selected.

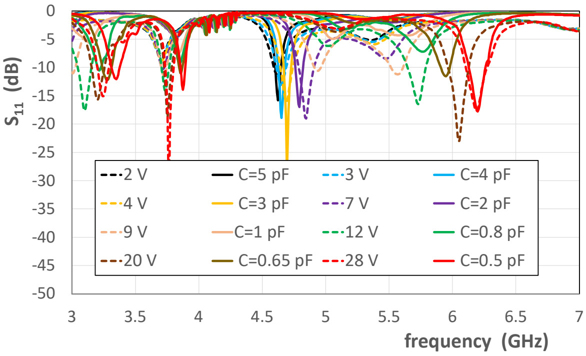


Fig. 5. The calculated (solid lines) and measured (dashed lines) S_{11} of the LWA array defined above. The pairs of lines of the same color represent S_{11} concerning to the applied DC bias and the varactor capacitance roughly corresponding to the dependence presented by the varactor producer [19].

The measured gain of the antenna array set to maximum value by the applied DC voltage is plotted in Fig. 6 as a function of frequency. Due to the gain value the antenna is applicable at frequencies around 3.25 GHz, where the gain is around 6 dBi and around 6.2 GHz, with the corresponding gain equal to about 4 dBi. Fig. 7 shows the measured span of the direction of the main lobe of the radiation pattern (elevation angle) $\Delta(\theta)$ set to maximum by the DC voltage biasing the varactors. Comparing the plots in Figs. 6 and 7, it is apparent that the maximum elevation angle span 20° corresponds to the maximum value of the gain at frequencies around 3.25 GHz and 6 GHz. These frequency points correspond to the minima of S_{11}, as seen in Fig. 5. The maximum elevation angle span 23° occurs at a frequency of 5.1 GHz but in an area of low gain equal to approximately -2 dBi, as shown by measurements.

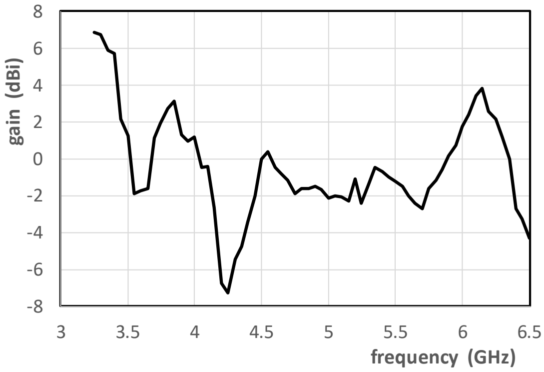


Fig. 6. The measured maximum value of the gain of the LWA array defined above.

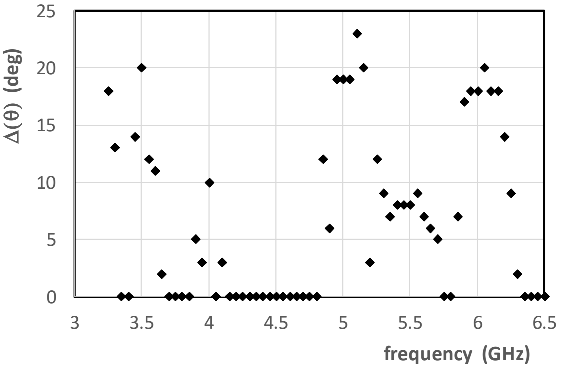


Fig. 7. The measured maximal span of the elevation angles reached by controlling the varactor capacitances by DC bias.

Radiation patterns calculated by CST MWS at 3.25 GHz (the frequency of the maximal gain) are plotted in Fig. 8 for different values of varactor capacitances. Negative angles correspond to forward radiation. Angle $\theta = 0°$ corresponds to broadside radiation. Fig. 8 shows an approximately 45° span of elevation angles for capacitance values varying from 0.5 to 0.8 pF. According to [19], this corresponds to DC voltages between 12 and 29 V. The radiation is in the RH mode, i.e., in the forward direction.

The varactor-controlled antenna array behaves at the selected values of voltage similarly as shown for the original LWA array [17] in the frequency domain. Direction of the maximum radiation is steered by increasing the frequency towards the forward direction.

The measured radiation patterns at frequencies of 3.25 GHz for the specified DC voltages are plotted in Fig. 9 in the voltage interval between 15 and 28 V. According to [19], this voltage span corresponds to a change of varactor capacitance between 0.5 and 0.75 pF, corresponding to the capacitance values used in Fig. 8. The plot in Fig. 9 shows antenna beam steered within an angle span of 20°. The maximum gain corresponds to the value already plotted in Fig. 6. The measured maximum of the span of elevation angles corresponds to the value shown in Fig. 7.

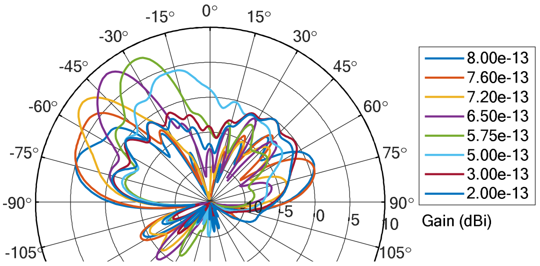


Fig. 8. Calculated radiation patterns (gain) of the LWA array defined above at frequency 3.25 GHz for particular varactor capacitances. The radiation is in the forward direction.

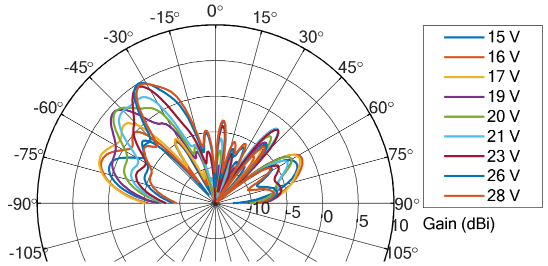


Fig. 9. Measured radiation patterns (gain) of the LWA array defined above at frequency 3.25 GHz and at DC varactor biases. The radiation is in the forward direction.

III. CONCLUSION

The paper used the LWA array presented in [17] as a pattern. That antenna has been redesigned into a reconfigurable array. The radiation pattern was controlled by DC voltage applied to varactors to change the elevation angle of the radiation pattern main lobe. The varactors were properly connected in parallel to the structure to allow their feeding by only one DC source. Simulation results were verified by experiments proving the functionality of the design. By changing the DC feeding voltage between 15 and 30 V, the designed LWA showed a change of the radiation pattern main lobe within 45° at 3.25 GHz, while measurement showed a change equal to only 20°. The work shows, however, the effective and simple way to obtain the reconfigurable antenna with its radiation controlled by DC voltage driving capacitances of applied varactors. The obtained results are comparable with most of data published in literature mentioned in Introduction. The measured maximum of the antenna gain is 6 dBi. The side lobe level is about -10 dB at the maximal applied voltage 28 V. The -3 dB frequency band is at this voltage equal to 150 MHz. The designed antenna has a simple structure that can be cheaply fabricated by PCB process.

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