Higher Spatial Harmonic Leaky Wave Antenna Design Based on Meandering Microstrips

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***Abstract*—A Leaky Wave Antenna (LWA) design with high scanning rate (the ratio of beam scanning range and bandwidth) is proposed in this work. The antenna is based on a periodic meandering microstrip line operating in K-Band with continuous beam scanning from backward-to-forward direction in the elevation plane. The height of the transverse lines is varied periodically in the unit cell to increase the electrical length. Hence, the antenna operates in higher spatial order which increases the scanning rate. The final antenna shows a scanning range in the elevation plane from –40° to 45° in the frequency range from 20.6 GHz to 24.6 GHz corresponding to a scanning rate of 21.25 ° GHz^{-1}. The antenna performance is compared with conventional meandering leaky wave antenna design to demonstrate notable increase in the scanning rate with very less impact on gain while also maintaining low profile.**

***Index Terms*—LWA, K-Band, higher spatial order, scanning rate, meandering microstrip antenna**

I. Introduction

Leaky Wave Antennas (LWAs) have frequency-dependent beam steering capability due to dispersion of the guiding media [1], [2]. Thanks to the easiness of fabrication, simple structure, low profile and low cost, microstrip based LWAs have received significant interest in the literature [3-13].

Microstrip LWAs generally operate in a fundamental spatial harmonic [3-7] or in a spatial harmonic of $n = -1$ [9-16]. Certain designs operating in higher spatial order of $n = -2$ based on Substrate integrated waveguides (SIWs) have also been proposed [17], [18]. In the present work, a new meandering microstrip design that operates in the spatial order of $n = -2$ is discussed. The consequence of operating in a higher spatial order results in faster scanning rate. A comparison with conventional simple meandering microstrip LWAs design [11-13] is also made to show the increase in scanning rate.

II. Antenna Structure and Concept of Operation

The design of the proposed LWA is shown in Fig. 1. The antenna operates in fundamental transverse electromagnetic (TEM) (EH_0) mode. The wave propagating along the microstrip line in the longitudinal direction (+Y-axis) can be classified by propagating constant γ [1], [19].

$$\gamma = \beta - j\alpha \quad (1)$$

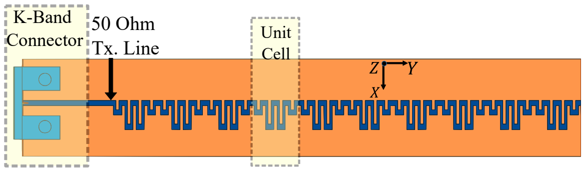


Fig. 1: Proposed LWA with 10 unit cells.

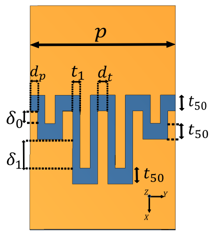


Fig. 2: Unit cell operating in spatial harmonic of $n = -2$.

where α denotes the attenuation constant and β denotes the phase constant.

Since the antenna is periodic, unit cell simulation as performed in [20], [21], is used to analyze the propagation and radiation characteristics of the guiding medium.

Fig. 2 and Table I report the dimensions of the unit cell for the proposed antenna design based on Rogers 3003 ($\varepsilon_r = 3$ and $\tan\delta = 0.001$). The following subsections highlight the rationale and subsequently the analysis of the optimised unit cell.

TABLE I
Optimised Dimensions of the Proposed Unit Cell

Parameter	Value (mm)
δ_0	0.33
δ_1	1.4
d_t	0.4
d_p	0.3
t_1	0.3
t_{50}	0.64
p	5.8
h_{sub}	0.254

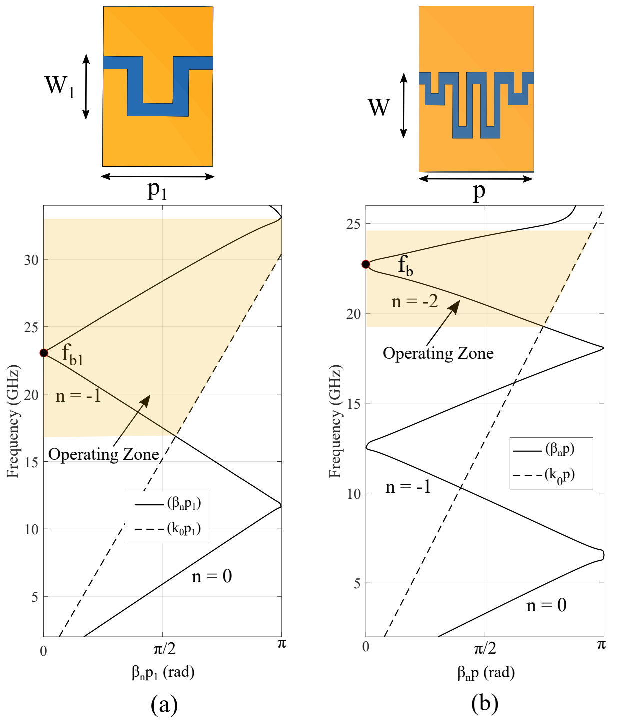


Fig. 3: (a) Brillouin diagram for the conventional unit cell operating in space harmonic of $n = -1$. and (b) for the proposed unit cell operating in space harmonic of $n = -2$. $f_{b1} = 22.6$ GHz and $f_b = 22.6$ GHz are the frequencies where radiation in broadside direction takes place. Here p_1 = 5 mm, W_1 = 2.8 mm and p = 5.8 mm, W = 3.01 mm.

A. Operation in higher spatial order

Due to the periodicity (p) of the structure, there exists an infinite number of space harmonics exist according to Bloch-Floquet theorem [19], [22], [23] propagating through the periodic meandering microstrip line. The phase constant of the n^{th} space harmonic β_n satisfies

$$\beta_n p = \beta_0 p + 2n\pi \tag{2}$$

where n = $-\infty$ to $+\infty$.

Fig. 3 shows the Brillouin diagram [1], [24] for the conventional unit cell design [11-13] in comparison to the proposed unit cell. The antenna radiates only when it operates in the fast wave region ($\beta_n p < k_0 p$) [19].

To enhance the scanning rate, the proposed structure operates in the spatial harmonic $n = -2$. This is achieved by adding transverse line segments of varying length of δ_0 and δ_1 (Fig. 2) and consequently the electrical path length of the unit cell. Fig.3 (a) and (b) show the conventional and proposed unit cell designs for K-band operation, together with the associated Brillouin diagrams. For the latter, the radiation associated to the second spatial harmonic (β_{-2}) occurs in the desired K-band frequency range.

B. Behaviour of leaky wave antenna

Table. I shows the design and dimensions of unit cell operating in a spatial harmonic of $n = -2$. The corresponding

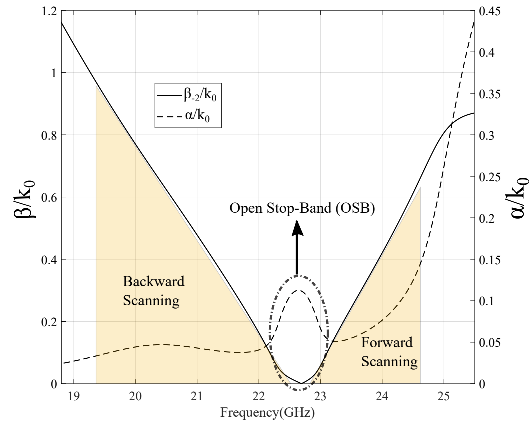


Fig. 4: Dispersion diagram extracted from driven-mode unit cell simulation. The antenna scans from backward direction (-Y-axis) to positive direction (+ Y-axis) predicted by the ratio of β and k_0. The ratio of α and k_0 predicts the beamwidth of the radiation pattern.

dispersion diagram is depicted in Fig. 4.

The antenna designed with this unit cell will radiate a narrow fan beam with the following characteristics.

The main beam direction θ_m is given by [18], [23], [25]

$$\theta_m = \sin^{-1}(\beta_{-2}/k_0). \tag{3}$$

where k_0 is the free space wave number

Qualitatively, large attenuation constant α results in a large leakage rate producing a short effective aperture, which will generally cause in a large beamwidth ($\Delta\theta$). Moreover, a narrow beam is due to low value of α resulting in long effective aperture. [1], [26].

A LWA operating in higher spatial order is designed with a substrate of height equal to 0.254 mm. 10 unit cells operating in $n = -2$ are cascaded to form the antenna as shown in Fig. 1 to obtain gain over 10 dB throughout the scanning range. The final antenna dimensions (excluding the connector) are 58 mm (length) × 10 mm (width) × 0.254 mm (height) hence making it quite compact.

III. K-Band Leaky Wave Antenna

A. Feed design and matching for the leaky wave antenna

In order to calculate the input impedance of antenna, the bloch impedance (Z_s) is obtained from the unit cell simulation using the same method as used in [26], [28]. The value of Z_s for the structure is close to $44\,\Omega$ in the the operating frequency range. Full-wave simulation of the LWA is performed in Ansys HFSS with a 2.92 mm end-launch Southwest connector that has impedance of $Z_0 = 50\,\Omega$ as shown in Fig. 5. The losses due to dielectric (α_d) is also accounted. The antenna array radiates a fan beam in the H-plane (Y-Z plane) that changes the angle of maximum radiation (θ_m) from backward (-Y) to forward direction (+Y).

TABLE II
COMPARISON WITH OTHER K-BAND AND KA-BAND SCANNING LWAS

Ref	Antenna Type	Frequency BW	Scanning Range	Gain (dB)	Rel. Permittivity (ε_r)	Scanning Rate (°/GHz)
[10]	Microstrip with metallized vias	20-29 GHz	95° (-50° to 45°)	Approx. 10	6.15	10.55
[27]	SIW	26-43 GHz	70° (-40° to 30 °)	13.4-15	3.0	3.04
[12]	Microstrip	37-57 GHz	95° (-45° to 50°)	10.8-13.8	3.0	4.75
This Work	Microstrip	20.6-24.6 GHz	85° (-40° to 45°)	9.8-13	3.0	21.25

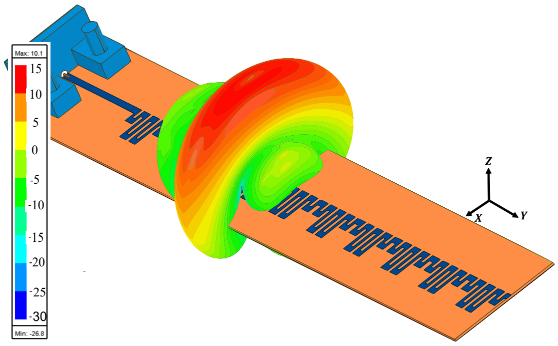


Fig. 5: Full Wave simulated fan-beam at f = 20 GHz. The gain of the antenna is shown and the scale is in dB.

B. Scanning rate enhancement of the proposed leaky wave antenna

To show the boost in scanning rate, a conventional LWA operating with spatial harmonic $n = -1$ (brillouin diagram described in Fig. 3(a)) with 10 unit cell cascaded with a periodicity of p_1 = 5 mm, is compared with the proposed antenna. The proposed antenna has a periodicity of p = 5.8 mm. As can be seen from the Fig. 6a and 6b, the proposed antenna scans a significantly large space (–40° to 45°) than the conventional design (–15° to 14°) for a similar operating frequency bandwidth of 4 GHz.

Although, there is an increase in electrical length of the antenna which enables operation in higher spatial harmonic, there is also an increase in physical length from p_1 = 5 mm to p = 5.8 mm

C. Performance of the proposed leaky wave antenna

The gain of the proposed antenna is nearly 10 dB throughout the operating frequency range shown in Fig. 6b.

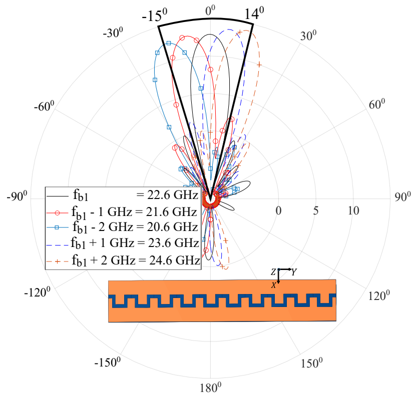
Table II shows the comparison with other LWAs in the similar operating frequency range. Notable increase in scanning rate is observed as compared to existing designs while also maintaining low profile.

IV. CONCLUSION

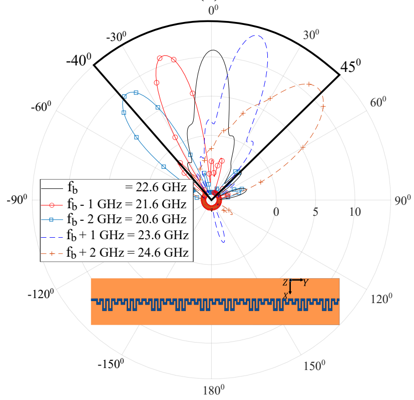
A novel microstrip based LWA operating in higher spatial harmonic of $n = -2$ is designed to enhance the scanning rate and expand the scanning range for a given operating frequency. A comparison with the previous existing design operating in $n = -1$ is also made showing that scanning rate of antenna can be increased by operating in higher spatial harmonic. The antenna is self-matched as well in operating frequency range presenting an impedance of 50 Ω except for the range where OSB exists. Hence there is no need of additional matching circuit.

Since the antenna is made up of simple meandered microstrip design with a single layer, it is easy to manufacture, robust and low profile.

Synthesis of the unit cell, elimination of open stop band (OSB) and measurements are out of the scope of this paper and will be expanded in future work.



(a)



(b)

Fig. 6: Variation in the angle of maximum radiation in the H-plane (Y-Z plane) for (a) conventional meandering microstrip LWA operating in spatial harmonic $n = -1$ and (b) proposed meandering microstrip LWA operating in spatial harmonic of $n = -2$. f_b and f_{b1} shown in Fig. 3 are the frequencies at which broadside radiation takes place. Both the antennae are linearly polarized in the H-plane

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