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A K_a-band Antenna based on an Enhanced Franklin Model for 5G Cellular Networks

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ABSTRACT

This paper presents a millimeter-wave antenna to cover 28- and 38-GHz bands recommended by Federal Communications Commission for the 5G cellular networks. The conventional narrowband Franklin antenna is modified geometrically to transform into a multiband antenna provided with a linear array arrangement to fit multiple patches in a compact assembly to achieve smaller form factor and improved gain profile. The suggested structural modifications are deployed to diversify the fundamental theory of Franklin antennas to generate wideband and multiple resonances. The measured results show an impedance bandwidth of 28-39 GHz covered by the three resonances. The realized gain is above 7 dBi in the complete range of operation, while the peak gain is 10.23 dBi at 36-GHz. The proposed antenna signifies its high potential to fulfill demands of 5G wireless systems.

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INTRODUCTION

Recent massive advancements in the information and communications technology (ICT), and an ever-increasing number of wireless devices and applications, have caused an erratic increase in the demand of high data rates and channel capacity. Available bands of the millimeter-wave (MMW) spectrum are suggested to be deployed for fifth generation (5G) networks with the aim to accomplish the requirements of wide bandwidth, low latency, and high data rates with the additional advantages of compact circuitries [1]. The projected transition towards the MMW bands would be able to facilitate the cellular service providers to increase the channel bandwidths beyond the already installed infrastructures [2]. Design and implementation of cellular networks at the MMWs is an unprecedented and massive task. At this spectrum, attenuations associated with signal propagation, atmospheric effects, and absorptions by obstacles become much severe as compared to currently deployed frequencies. Hence, it is of crucial importance to redesign the network into clusters of smaller cells; i.e., ultra-dense networks (UDNs); which leads to minimal path losses, as well as provision of unique features based on the MMW techniques. The implementation of the advanced subsystems using the efficient deployment of the radio frequency (RF) channel modelling and link budget analysis, results in the improved quality of service (QoS), as well as the enhancement of the network capacity and coverage [3, 4].

Federal Communications Commission (FCC) has announced new set of rules to establish 5G frameworks and permitted the unused bands of 28-GHz, 37-39 GHz, and 64-71 GHz as potential candidates for 5G due to relatively lower propagation losses than other MMW frequencies. Declaration of 5G bands has aggravated a need for efficient antennas capable of simultaneous operation in the intended bands, to ensure the optimal access to the spectrum. Antenna design is one of the key considerations for the appropriate development of 5G architectures, particularly for mobile network industry. Numerous efforts have been reported to specify MMW antenna design parameters, such as bandwidth, handset effects, gain coverage, hardware integration complexity, smaller form factor and installation cost [5, 6]. It is highly desired that antenna device operates in a huge frequency range to support a wide range of applications and services with minimal latency. In this paper, a compact multiband antenna has been proposed at K_a-band to cover specifically 28-GHz and 37-39 GHz. The dimensions of the developed antenna are compatible to be fitted in mobile phones and other hand-held devices.

A conventional Franklin array is designed as a linear array, where radiating elements of $\lambda/2$ length are connected by means of quarter-wave ($\lambda/4$) phasing stubs. This configuration results in the development of a linear and compact array which offers high gain and directivity, yet restricted to narrow bandwidth operation [7, 8]. Franklin antenna is fundamentally designed for a single resonance, as the dimensions of each segment are specified based on the resonant frequency. Substantial efforts have been made to improve the bandwidth of Franklin arrays which results in higher degree of complexity in the design [9], as well as a compromise in the compactness of the structure [10]. The foremost emphasis of this work is to deploy the simplicity of this structure for 5G cellular antennas, and to diversify and extend the concept of Franklin array with additional resonant bands. This has been fully conducted by proposing an enhanced Franklin model, in order to achieve a multiband operation in the FCC-suggested MMW frequency bands.

ANTENNA DESIGN AND FABRICATION

A Franklin antenna consists of a series of radiating patches of $\lambda/2$ length interconnected by means of transmission lines of $\lambda/2$ length, and further folded to make $\lambda/4$ long non-radiating stub segments; to avoid mismatch due to discontinuity. The folded arrangement minimizes the area required to integrate matching network between consecutive patches and results in a smaller foot print. The radiation pattern shows a collective radiation collimated from each segment to constitute a main radiating beam in the broadside direction. As the structure is designed entirely based on λ/2 segments of resonant frequency, the antenna offers single frequency operation. Moreover, in order to modify the antenna operation into multiband or wideband, the proposed approach is to transform the non-radiating phasing stubs as the radiating antennas. This is done by changing the total length of the folded stub from λ/2 (i.e., in the Franklin antenna) to λ/3 (i.e., in the proposed one). Here, the design frequencies are 5G bands, therefore, the patch length is associated with λ/2 of 38-GHz resonant frequency, and length of folded stub is designed as λ/3 of 28-GHz. In order to achieve band I (i.e., 28-GHz) resonance, mean-average length (i.e., L_{avg}) of the folded stub is calculated by averaging the outer and inner lengths of the stub. The fringing field effects are considered based on the transmission line (TL) model to compute the radiating length of the folded stub, which is λ/3 of the resonant frequency. Similarly, for band II (38-GHz), the effective patch length is related to λ/2 of the resonant frequency.

The designed antenna geometry incorporates six unit cells, which are arranged in a linear array configuration. Each unit cell is comprised of two radiating structures, i.e., the patch and the folded stub. Absence of a phasing network causes an impedance mismatch at the terminating edges of each radiating element, which can be improved by adjusting the patch width, gap, and width of the folded antenna. Fig 1 (a) presents a MMW multiband antenna of size 12.6 × 30 mm^2 designed by using the CST STUDIO SUITE software. The details of design parameters, as well as the optimized dimensions are provided in Table I. The antenna is fabricated on a 0.8 mm thick substrate of Rogers RT/duroid 5880 (ε_r = 2.2, tanδ = 0.0009) provided with 17.5 µm thick copper cladding. The interconnected array of unit cells is then fed with a single feeding stub of length 2.25 mm. The LPKF laser machine is effectively employed to achieve a precise prototyping on the substrate, as fabrication accuracy is extremely important at MMWs to avoid frequency shifts. The fabricated prototype mounted with a 50Ω *K*-connector is presented in Fig. 1 (b).

RESULTS AND DISCUSSIONS

The performance of the developed 5G antenna is investigated based on the scattering (*S*)-parameters, radiation pattern, and realized gain profile. The measured results are in a good agreement with the simulations, and therefore validate the numerical evaluations performed in the software. Simulated and measured S_{11} plots of Fig. 2 depict the operating bandwidth of the proposed antenna at the 28-GHz (i.e., 27.9-33.2 GHz), and 37-39 GHz (i.e., 34-39.1 GHz) which covers the FCC-allocated 5G bands. Parametric study has been carried out in order to analyze the frequency tuning parameters of the two resonating bands. This thorough MMW study suggests that L_s controls the resonant frequency of band I, while band II can be tuned by changing L_p. Figs. 3 (a) and (b) present the parametric analysis carried out in simulations to illustrate the mentioned scenarios. The co- and cross-polarized far-field radiation patterns are shown in Fig. 4 at three frequencies, which depict a close match between simulations and measurements. The main beam in band I is along the boresight direction and tilted towards end-fire direction at an angle of 30˚. In band II, the maximum radiation is along the end-fire direction in 36-38 GHz with grating lobes, and exhibits a response similar to a leaky-wave antenna (LWA). Table 2 provides the realized gain at the distinct frequencies of the operating range. Reasonable gain profile has been achieved over a wide operating range of K_a-band.

CONCLUSION

This investigation has thoroughly undertaken a novel approach to develop a multiband MMW element based on a proposed enhanced Franklin array model, for the potential employment in the 5G cellular networks. The standard theory of Franklin antenna is diversified by designing the geometrical modifications, in which the conventional non-radiating phasing stub of λ/2 length has been transformed into the radiating stub of λ/3 length. The antenna is designed to operate in the FCC-approved 5G bands, and offers high gain profile and smaller form factor suitable for compact integration. Parametric study based on the radiating lengths has provided the ability to tune the frequency of any operating band, which effectively adds another degree of freedom into the systematic design framework. The multiband enhanced Franklin antenna offers distinguishing performance attributes, as required by the advanced paradigm shift which is currently undergoing for the K_a-band 5G-centric communication architectures.

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FIGURE CAPTIONS

Fig. 1 MMW multiband 5G antenna: (a) Simulated model in the software, (b) Fabricated antenna prototype

Fig. 2 Simulated and measured S_{11} plots MMW multiband 5G antenna.

Fig. 3 Parametric analysis of the MMW multiband 5G antenna: (a) Frequency of band I can be tuned by length of stub, L_s, (b) Frequency of band II can be tuned by patch length, L_p.

Fig. 4 Co- and cross-polarized radiation patterns of the 5G antenna.

TABLE CAPTIONS

Table 1: Optimized dimensions of the MMW 5G antenna.

Table 2: Realized gain vs. frequency of the MMW 5G antenna.

Figures

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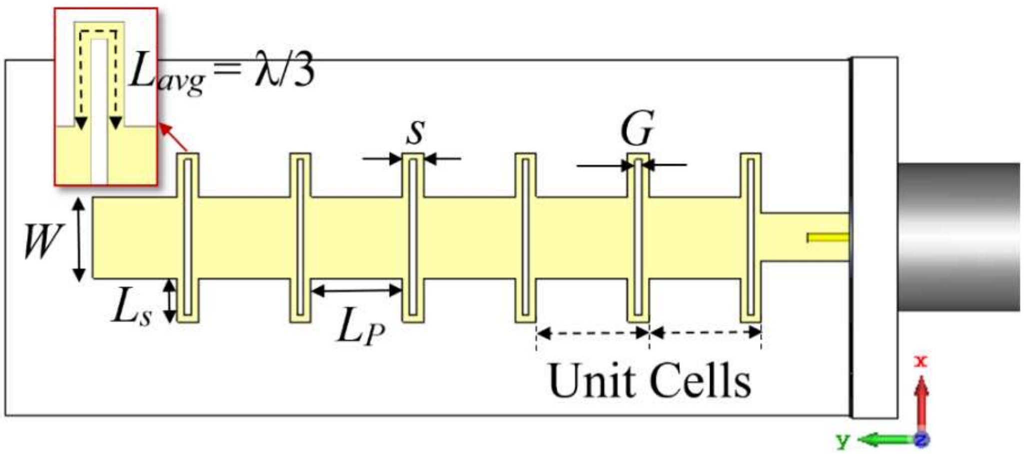

Fig.1. (a)

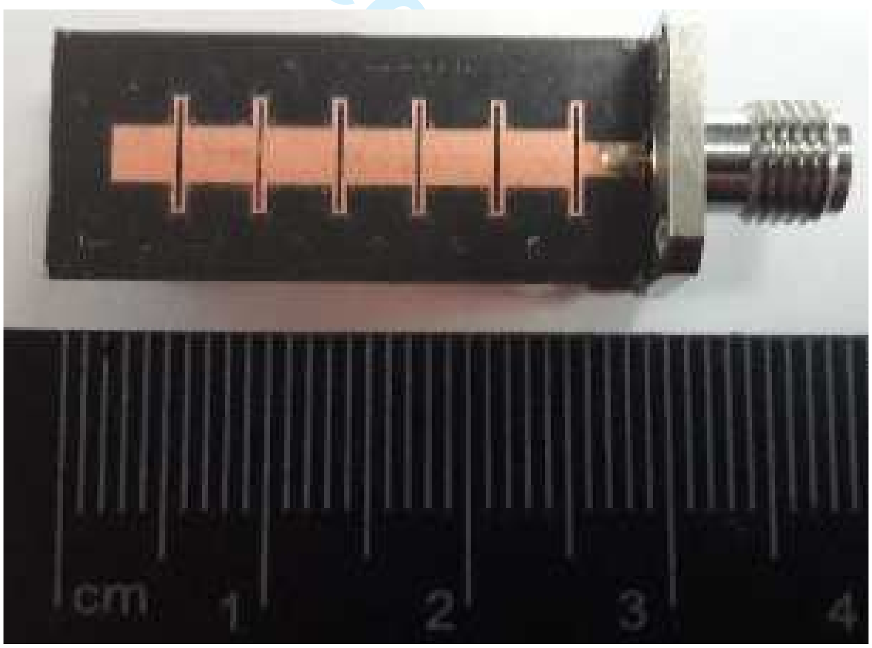

Fig.1. (b)

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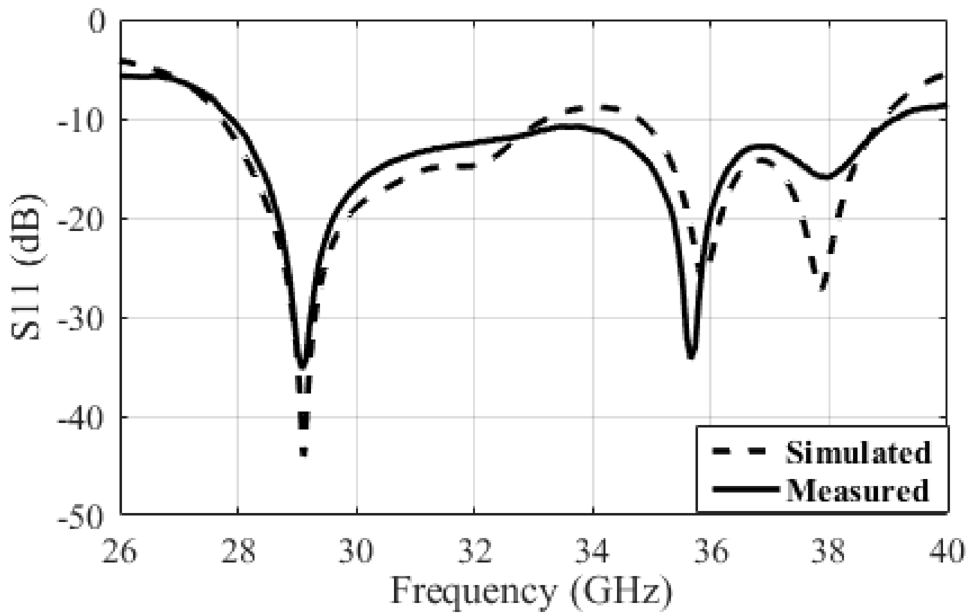

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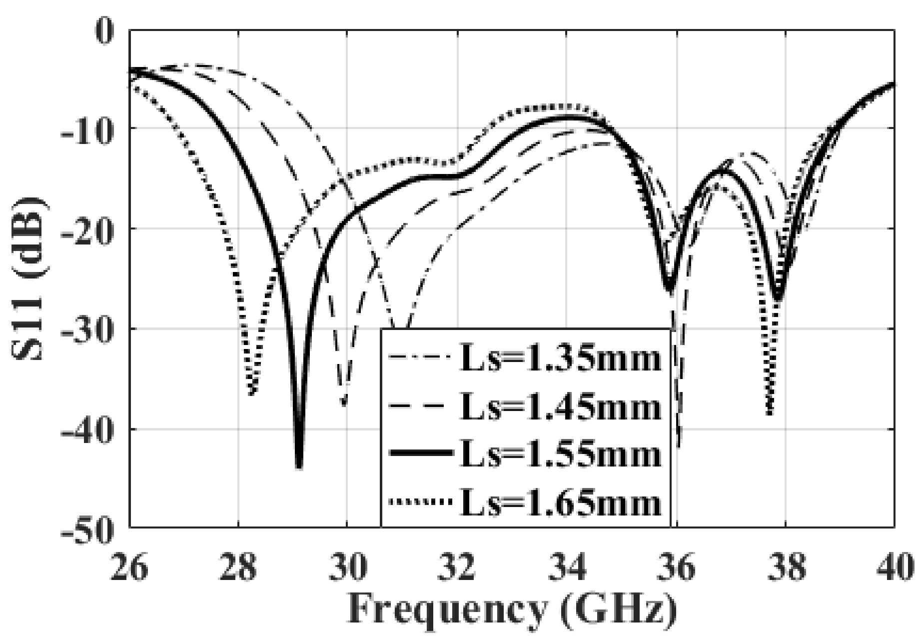
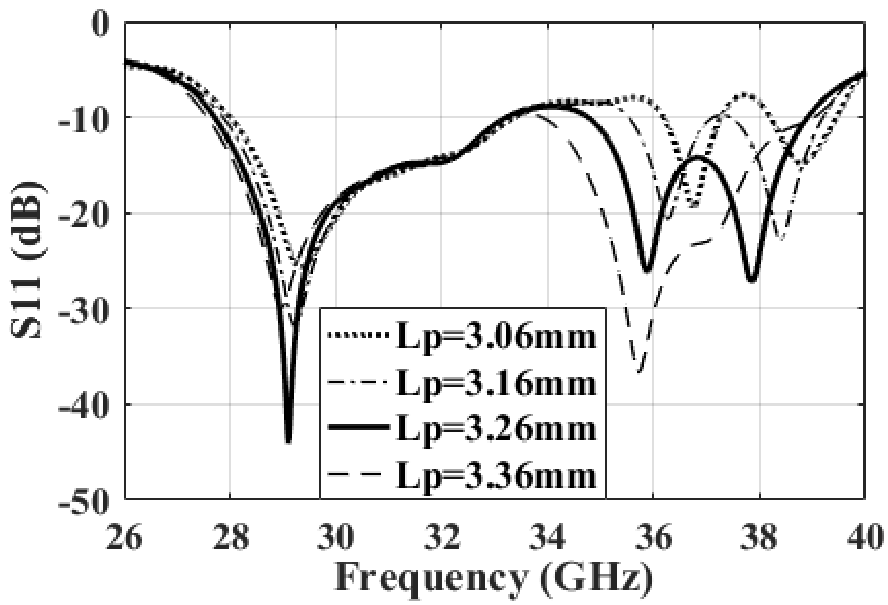


Fig.3 (a)



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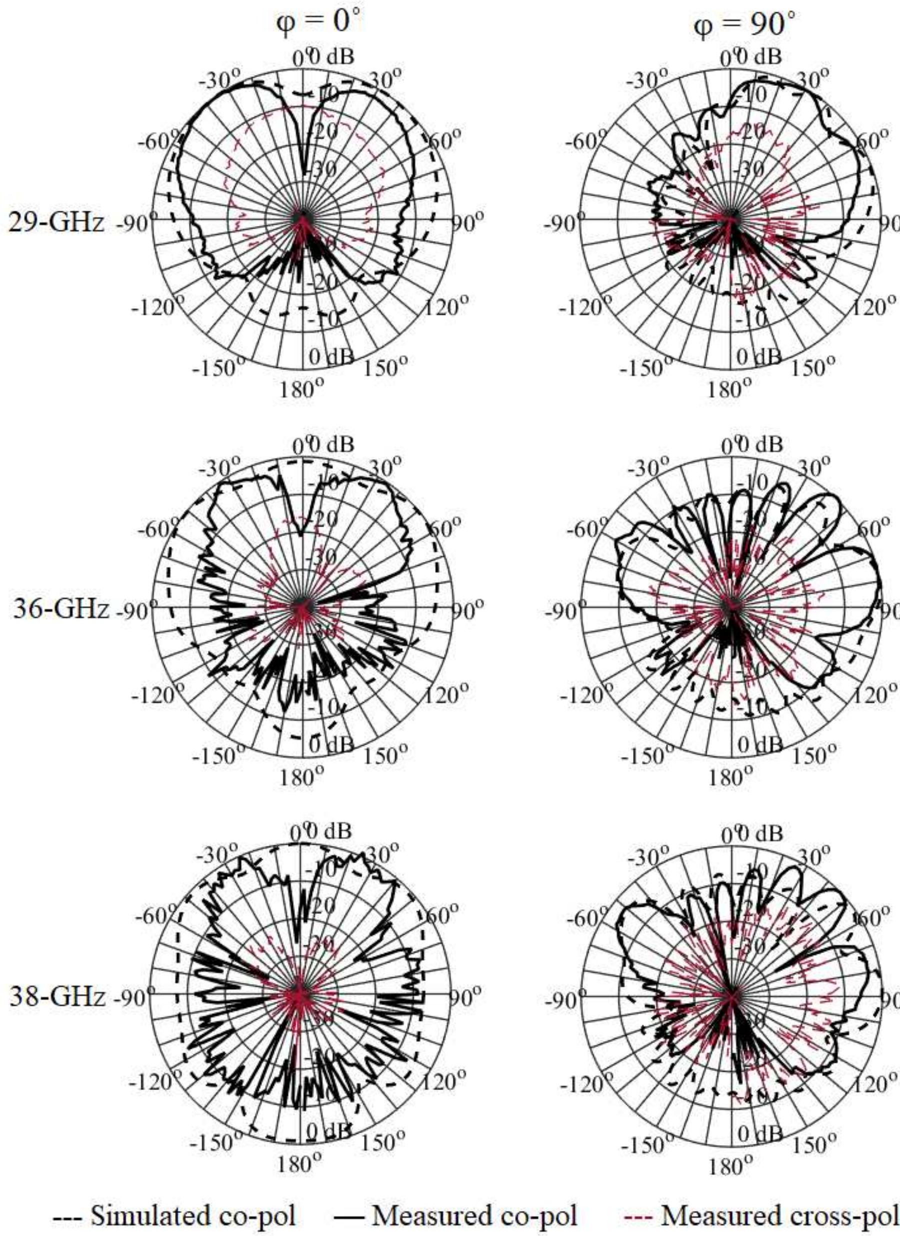

Fig. 4 Co- and cross-polarized radiation patterns of the 5G antenna.

Tables

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Table 1: Optimized dimensions of the MMW 5G antenna.

Parameter	***mm***	***Parameter***	***mm***
Length of patch, L_p	3.26	Width of patch, W	2.9
Length of stub, L_s	1.65	Width of folded stub, s	0.74
Mean length of folded stub, L_{avg}	3.54	Gap of folded stub, G	0.24

Table 2: Realized gain vs. frequency of the MMW 5G antenna.

Frequency (GHz)	***28***	***30***	***32***	***34***	***36***	***38***
Simulated gain (dBi)	7.15	7.91	8.19	8.81	10.09	9.9
Measured gain (dBi)	7.2	7.64	7.94	8.68	10.23	9.8