

Dual-Band Dual-Polarized Antennas for 5G mmWave Base Stations

Thi H. Le,^{1,*} Ivan Ndip,^{1,2} and Martin Schneider-Ramelow^{1,3}

Abstract—In this paper, we present a systematic approach for the development of application-specific antennas for 5G millimeter-wave (mmWave) base stations. First, an in-depth analysis of 5G mmWave base stations considering the required antenna gain and antenna elements to address different equivalent isotropic radiated power requirements is presented. This is followed by an evaluation of the realistic impact of different factors, which affect mmWave communication, namely output power of power amplifiers, antenna gain, losses and weather condition (rain), on transmission ranges between base station and terminals, considering the link budget analysis for an Urban Macro cell with the Non-Line-of-Sight transmission, as an example. Finally, based on a comparative analysis of published dual-band dual-polarized 5G mmWave antennas, we propose a novel configuration of a dual-band dual-polarized antenna for 5G mmWave base station applications, which overcomes the limitations of conventional antennas in published literature. Our proposed antenna covers the specified 3 GHz bandwidths in the 5G mmWave n257 and n260 bands and reaches approximately 6 and 6.7 dBi, respectively in these bands. Furthermore, it exhibits at least 20 dB isolation between the polarizations and has dimensions of $1.8 \times 1.8 \times 1.2$ mm. We modeled, simulated, fabricated, measured and analyzed this new antenna configuration. Excellent correlation is obtained between measurement and simulation results.

Keywords—5G mmWave antennas, antenna-in-package, antenna measurements, base station antennas, dual band dual polarized antennas, link budget analysis

INTRODUCTION

Since the first generation (1G) of mobile communication technology was introduced in 1981, a new generation has been launched approximately after every 10y. From 1G to 4G, mobile communication networks and systems have been designed to operate in sub-6 GHz bands. However, because of the narrow bandwidths at sub-6 GHz bands they can no longer support emerging high-speed applications, which require larger bandwidths.

Therefore, millimeter-wave (mmWave) frequency bands e.g., at 28 and 38 GHz (FR2), each exhibiting an operational bandwidth of 3 GHz, have been standardized for the fifth

generation (5G) of mobile communication to enable multi Gbits/s data rates. Moreover, due to short wavelengths at mmWave bands, a high degree of miniaturization of mobile communication devices can be achieved because most of the system components (e.g., antennas) scale directly with wavelength. However, the development of mmWave systems is very challenging, partly due to very high free space attenuation, which may deteriorate the transmission quality and range. To overcome this problem, new signal processing concepts and system architectures, e.g., mmWave (massive) MIMO (multiple input multiple output), have been proposed. The hardware implementation of these new concepts for 5G mmWave requires advanced packaging technologies [1]. This implementation is especially important for base stations (BST), since they have to address 10s and 100s of users at different distances from a base station. 5G BST can be categorized into four types, namely femto/picocell, small cell, micro base station/mmWave BST, and macro base station [2].

Some of the key components required for the development of these BST are antennas. So far a wide variety of antenna configurations has been proposed for 5G mmWave applications. The focus of most of the published works has been on (1) developing single-band antennas with improved impedance bandwidth using stacked patch [3] or U-slot configurations [4, 5], (2) studying different dual-band antenna configurations at 28/38 GHz frequency bands such as slot rectangular patch [6], planar inverted-F antennas [7], substrate integrated waveguide antennas [8], printed slot [9], and (3) generating polarization diversity/reconfigurability e.g., in [10–12]. However, to the best of the authors' knowledge, there is no published work in which an application-specific design approach for the development of scalable, miniaturized, high gain and broadband antennas for 5G mmWave BST has been discussed.

In this article, we present a systematic approach for the development of application-specific antennas for 5G mmWave BST. First, an in-depth analysis of 5G mmWave BST considering the required antenna gain and antenna elements to address different EIRP (equivalent isotropic radiated power) requirements is presented. This is followed by an evaluation of the realistic impact of different factors, which affect mmWave communication, namely output power of power amplifiers, antenna gain, losses and weather condition (rain), on transmission ranges between base station and terminals, considering the link budget analysis for an urban macro cell (UMa) with the Non-Line-of-Sight (NLOS) transmission, as an example. Finally, based on the results from the link budget analysis and the comparative analysis of published dual-band dual-polarized

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5G mmWave antennas in three main aspects (performance, integration density, and polarization coupling requirements), we propose a novel configuration of a 28/38 GHz dual-band dual-polarized antenna for 5G mmWave base station applications, which overcomes the limitations of conventional antennas in published literature. In addition, the impacts of different antenna parameters on the antenna resonance frequency, impedance matching, and bandwidth are investigated and analyzed. Our proposed antenna covers the specified 3 GHz bandwidths in the 5G New Radio (NR) n257 and n260 bands, reaches about 6 and 6.7 dBi, respectively in these bands, exhibits at least 20 dB isolation between the polarizations and has dimensions of $1.8 \times 1.8 \times 1.2$ mm. We modeled, simulated, fabricated, measured and analyzed this new antenna configuration. Excellent correlation is obtained between measurement and simulation results.

The remaining sections of this paper are structured as follows: in the Overview of 5G base stations section, an overview of 5G BST is given. A link budget analysis is presented in the Link budget analysis section, and in the Dual-band dual-polarized antenna section an in-depth analysis of published antennas for BST as well as our proposed antenna configuration is presented.

OVERVIEW OF 5G BASE STATIONS

A telecommunication infrastructure in general and a 5G mobile communication network in particular consists of four parts, namely end devices, radio access networks (RANs), core networks, and transport networks. RANs include BST, which serve as central connection points for wireless connectivity between end devices and core networks connected to the internet. 5G BST are categorized into four types, namely femto/picocell, small cell, micro base station/mmWave BST, and macro base station [2]. From [2] and [13] an overview of different 5G base station configurations is summarized in Table I.

In 5G networks, already existing 4G macro cells (cell towers) are upgraded to provide an effective coverage in a wider area. In addition, based on the advantages of small cells (i.e., smaller size, low cost and power consumption), a new trend in 5G networks is to densify small cells for increasing data capacity. The base station configurations are addressed depending on the desired throughput, the area of the cell, and its location. Femto/pico cells and small cells have low output

power and operate mostly at the mmWave frequency range FR2. Hence, they are more suitable for indoor applications. Micro and macro BST are first designed to operate in the sub-6 GHz band (FR1) and used for outdoor applications with long transmission distances (e.g., dense urban areas). In the long term, mmWave frequency bands will be also added to these large base station configurations to form mmWave BST. Three mmWave frequency bands at 26, 28, and 38 GHz have been specified for this purpose. Following the U.S. where mmWave in both 28 and 38 GHz bands was the first 5G platform, Japan also started the first 5G mmWave systems at 28 GHz in mid2020. The 28 GHz frequency band has also been used in Korea for 5G mmWave since early 2021. The adoption of 5G mmWave will be delayed in China since the main focus in the country is to have a strong rollout policy using sub-7 GHz bands and licensed 6 GHz band. At the 26 GHz band the first commercial mobile 5G mmWave network was launched in the EU in 2023 [2, 14, 15].

LINK BUDGET ANALYSIS

A base station includes transmitters and receivers, which consist of antennas, radio frequency (RF) chains and basebands. To increase the system performance (i.e., data rates and reliability) of 5G wireless transmissions, the concept of massive MIMO antenna systems, and which include a very large number of independently operating antenna elements, is required. To get a proper division between the RF and the digital domain, hybrid beamforming (HBF) architectures have been developed for 5G. In Fig. 1, an example of an HBF-based massive MIMO transmitter architecture for 5G is presented. It consists of a sub-6 GHz module and an mmWave module. Such system architecture can be used to develop 5G base station configurations shown in Table I. In this work, we focus on 5G mmWave BST.

One of the fundamental questions that need to be addressed when developing a base station is regarding the total required antenna gain and number of antenna elements, respectively. To get the first estimate of the required number of antennas for different 5G BST, a simple link budget analysis for calculating the total transmit antenna gain (G_{TX}) can be carried out based on the given output power of the power amplifier (PA) (P_{out}), the transmission loss from IC (integrated circuit) output to

Table I
Overview of Different 5G Base Station Configurations [2, 13]

BS configuration	Femtocells/picocells	Small cells	Micro base station/ mmWave BS	Macro base station
Frequency region	mmWave (FR2)	mmWave (FR2), sub-6 GHz (FR1)	mmWave (FR2), sub-6 GHz (FR1)	mmWave (FR2), sub-6 GHz (FR1)
Location	Indoor, outdoor	Indoor, outdoor	Outdoor	Outdoor
Application area range	Residential and office buildings	In multiple places all cross dense urban areas, on lamp posts, on road signage, or bus stops	Dense urban areas	Suburban, city, and rural area
Range	5-20 m	5-100 m	100-2,500 m	2 → 25 km
Power	0.02-1 W	1-10 W	10-160 W	80 → 480 W
EIRP	13-30 dBm	30-40 dBm	40-52 dBm	49 → 57 dBm
Typical number of users	1-100	100-1,000	1,000-2,000	>2,000

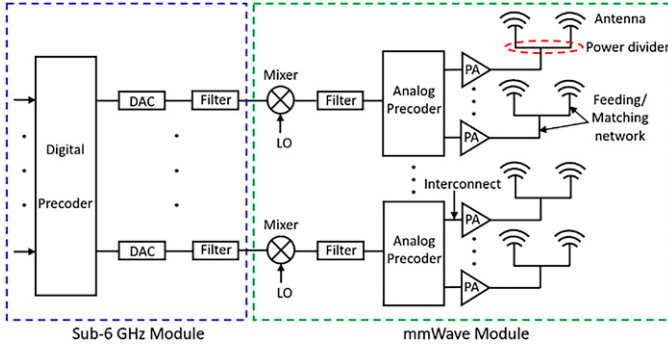


Fig. 1. An example of an HBF-based MIMO transmitter architecture [1].

antenna input (L_t) and the specified EIRP (see eq. 1).

$$\text{EIRP} = P_{\text{out}} - L_t + G_{\text{TX}} \quad (1)$$

The value of P_{out} depends on the chip technology of power amplifiers. In Fig. 2 we show a RF transistor and RF IC technology chart. Silicon-or III-V-based technologies such as gallium nitride (GaN) and indium phosphide are suitable for small-size PA development of mmWave BST and user terminals (UT). As can be seen in this figure RF complementary metal-oxide-semiconductor (CMOS) technology gives the lowest output power (about 13 dBm in [16]), while with GaN technology the highest power (about 30 dBm) can be achieved. However, the higher the chip performance, the more expensive it becomes.

Assuming that the system architecture in Fig. 1 is used for the development of the base station configurations in Table I at 28 GHz, L_t is about 1-2 dB, and one PA feeds two antenna elements, we used eq. (1) to calculate the number of antenna elements and PAs required for each 5G BST type. For the link budget analysis, we choose two representative output powers of PAs based on RF CMOS and GaN, namely +13 and +30 dBm at 28 GHz. The results are shown in Table II. This table shows that an antenna array of 256 elements is required for the macro cell base station when GaN technology is used to develop PAs. This number increases by 64 times with CMOS technology. From these results, it can be seen that the CMOS PAs are more suitable for low-power BST such as femto/pico cells or small cells. For micro and macro cell BST high power PAs are required to reduce the load for the antennas. This calculation gives the approximate number of required antennas

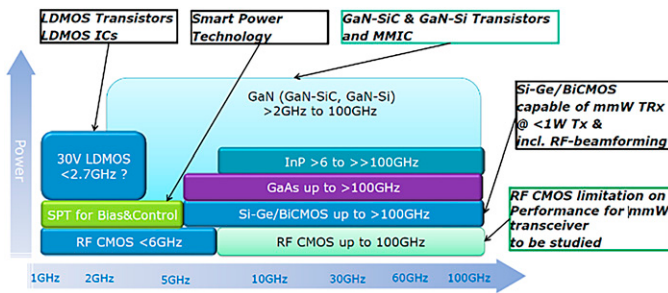


Fig. 2. RF transistor and RF IC technology chart (<https://serena-h2020.eu/downloads/IMS2019-Overview-about-RF-and-PA-Requirements-for-5G-NR-Franz-Dielacher.pdf>).

and PAs without considering the achieved transmission distance. The achievable range from a base station to end devices depends strongly on the path losses, which have different values at different scenarios, topographic, environment, and weather conditions.

In [17], path losses for different scenarios without considering attenuation due to oxygen absorption are presented by 3GPP. In this section, we focus on a link budget analysis for an UMa with the NLOS transmission, as an example. A typical height of a macrocell BST, h_{BS} is 25 m. The height of a user terminal, h_{UT} varies between 1.5 and 22.5 m. $d_{2\text{D}}$ is the so-called intersite distance (ISD) between BST and UT. The definition of the 3D distance between BST and UT ($d_{3\text{D}}$) for outdoor user terminals is indicated in eq. (2).

$$d_{3\text{D}} = \sqrt{d_{2\text{D}}^2 + (h_{\text{BS}} - h_{\text{UT}})^2} \quad (2)$$

Assuming h_{UT} is 3 m and we consider the distance $d_{2\text{D}}$ in the range between 250 and 2,000 m, then $d_{3\text{D}}$ is approximately equal to $d_{2\text{D}}$. The full path loss for this scenario is determined as follows (see eq. 3).

$$\text{PL}_{\text{UMa-NLOS}} = 13.54 + 39.08 \log_{10}(d_{3\text{D}}) + 20 \log_{10}(f_c) - 0.6(h_{\text{UT}} - 1.5) \quad (3)$$

where f_c is the carrier frequency.

Based on eqs. (2) and (3), the dependence of path loss on different ISDs for the NLOS urban macrocell BST at three frequencies, namely 26, 28, and 38 GHz, is plotted in Fig. 3. The plot shows that with a distance of 2 km the path loss of this scenario can be up to 175 dB.

In eq. (4), a link budget calculation at mmWave considering the transmission distance and power level at BST and UT side is presented.

$$P_{\text{out}} + G_{\text{TX}} - L_t - \text{PL} = -G_{\text{RX}} + \text{SNR}_{\text{RX}} - L_{t,\text{RX}} \quad (4)$$

As an example, we analyze a transmission link budget at 28 GHz, at the “worst” case scenario for an UMa-NLOS (see Fig. 4).

The current legacy mmWave radio emission (EIRP) of macrocell BST is 60 dBm (see Table I). In this case, for an ISD between BST and user terminal of 300 m, the full path loss of NLOS is around 138 dB at 28 GHz. Assumed that PAs based on GaN technology with an output power of 30 dBm is used. An antenna array of 256 elements with a total gain of 31 dBi is required. The transmission loss L_t is approximately 1 dB. If the antenna gain of the user side is 10 dBi, the single-to-noise ratio (SNR_{RX}) at user terminal should be lower than -69 dBm.

Fig. 5 presents the total required antenna gain at BST G_{TX} as a function of the link distance with the “worst” case of SNR and gain at the user terminal of -69 and 10 dBi, respectively, for three 5G mmWave frequencies 26, 28, and 38 GHz. The plot shows that the transmission distance between BST and UT increases with the transmit gain of BST and reduces with the frequency. A link distance of 300 m is achievable with G_{TX} of about 30 dBi at 28 GHz. With the gain of 80 dBi, this distance could increase up to 6 km.

To illustrate the influence of weather conditions on the mmWave transmission, we evaluate two application cases with and without 25 mm/h rainfall at 28 GHz. For the case without

Table II
Number of Required PAs and Antennas for Different Base Station Types at 28 GHz

BS configurations	Femtocells/picocells	Small cells	Micro base station/mmWave BS	Macro base station
EIRP	29 dBm	40 dBm	52 dBm	60 dBm
Total antenna gain CMOS/GaN	17/0 dBi	28/11 dBi	40/23 dBi	48/31 dBi
Gain of a single antenna	6 dBi	6 dBi	6 dBi	6 dBi
Number of PAs CMOS/GaN	8/1	128/2	2,048/32	8,192/128
Number of antenna elements CMOS/GaN	16/1	256/4	4,096/64	16,384/256

rain, the value of water absorption below 30 GHz is not significant (0.1 dB/km) and thus can be neglected. Heavy rain of 25 mm/h induces an attenuation of 7 dB/km at 28 GHz [18].

Fig. 6 shows the dependence between path loss, required gain G_{TX} and different ISDs at 28 GHz for two cases with and without rain. The impact of rain becomes more significant in long transmission distances. For an ISD of 2 km, the difference in path loss and gain between two cases is 14 dB(i). In other words, the achievable range with the same antenna gain is reduced in rain. For example, the signals with $G_{TX} = 60$ dBi can be transmitted up to 1.6 km in good weather. When there is rain, this distance decreases to 1.2 km.

Besides the antenna gain, the antenna bandwidth has also a significant impact on the channel capacity, which represents the amount of information that can be transmitted over a communication channel. According to Shannon's theorem (eq. 5) the channel capacity increases proportionally with the antenna bandwidth.

$$C = B_n \cdot \log_2 \left(1 + \frac{P_{RX}}{B_n \cdot N_{Power}} \right) = B_n \cdot \log_2 (1 + \text{SNR}) \quad (5)$$

where B_n is the antenna bandwidth, P_{RX} is the received power, N_{Power} is the noise power, and SNR is the signal-to-noise ratio.

DUAL-BAND DUAL-POLARIZED ANTENNA

Investigations in the previous section show that high gain and broadband antennas are required for 5G mmWave

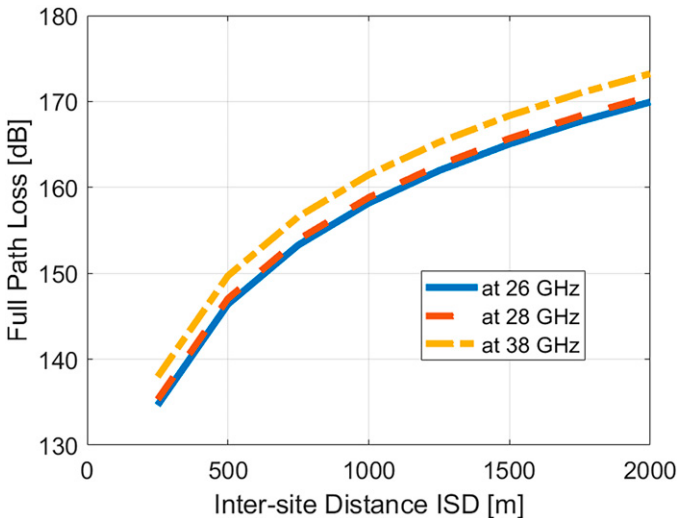


Fig. 3. Path loss for different ISD.

communication systems in order to improve the transmission ranges and the data rates, respectively. Furthermore, the integration aspect plays a paramount role, since the antennas will be later integrated together with other active/passive elements e.g., in a package (i.e., antenna-in-package [AiP]). Based on these requirements, we propose in this section our modeling, simulation, measurement and analysis of a novel dual-band dual-polarized antenna operating at 28/38 GHz for the development of AiP modules for 5G mmWave BST.

A. State of the Art

As the name implies, dual-band dual-polarized antennas are developed to operate in two different frequency bands, one at the time or simultaneously, and have two polarizations. Fig. 7 shows examples of dual-band dual-polarized antennas. Such antenna configurations do not only exhibit multiple characteristics, but can also improve channel capacity without adding additional antennas, and thus increase the reliability of wireless transmission significantly. Their dual polarization characteristic can help to reduce the polarization mismatch, which may occur during transmission, and is also very useful in mitigating multipath fading. Moreover, the use of dual-polarized antennas at BST could reduce the design challenges on antennas at the corresponding end terminals. Finally, these antennas need only small space for operating in two frequencies. This enables a reduction of the installation space and thus reduces the installation cost.

Due to their multiple advantages, dual-band dual-polarized antennas received significant research attention for 5G mmWave. Examples of publications on this antenna configuration for 5G are given in Table III. In this table, the antennas are compared considering three main criteria, namely performance, integration possibility, and polarization coupling. Regarding the performance aspect, a wide impedance bandwidth of 3 GHz is required to cover the full specified bandwidth in 5G mmWave bands. Meanwhile, antenna dimensions (i.e., substrate thickness and lateral dimensions) are directly related to the integration possibility of antennas into an AiP platform. Since the antenna configuration

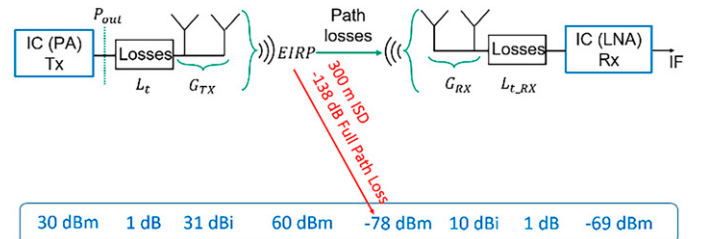


Fig. 4. mmWave transmission link budget at 28 GHz.

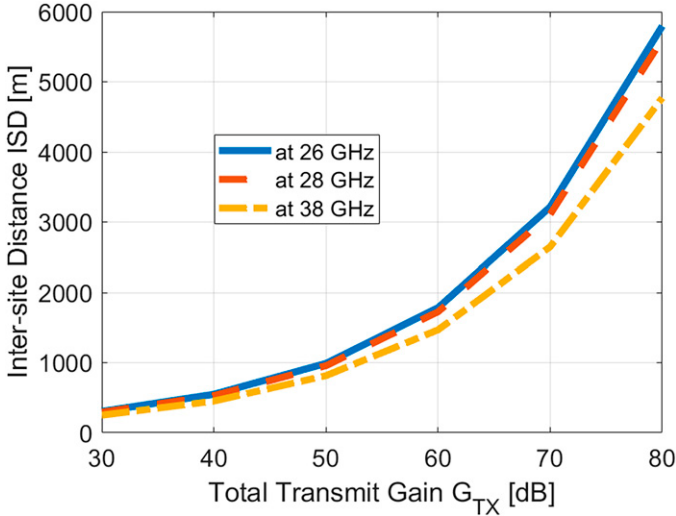


Fig. 5. Required total transmit antenna gain versus link distance with certain system parameters.

has a dual polarization characteristic, the isolation between two polarizations is also taken into account. Therefore, the comparison in this section will focus on three key parameters:

1. 3 GHz bandwidth, considering both simulation and measurement results
2. Dimensions of antenna (i.e., substrate thickness and lateral dimensions)
3. Polarization coupling

As can be seen in Table III, none of these published antenna configurations is fabricated and measured. Compared with these antennas, our proposed dual-band dual-polarized antenna exhibits not only an impedance bandwidth of at least 3 GHz and a low mutual coupling of less than -20 dB at both frequency bands 28 and 38 GHz, but has also a high gain (above 6 dBi) with smaller antenna dimensions. This enables the antenna to be scaled to (massive) MIMO antenna arrays to address different EIRP requirements of 5G mmWave BST.

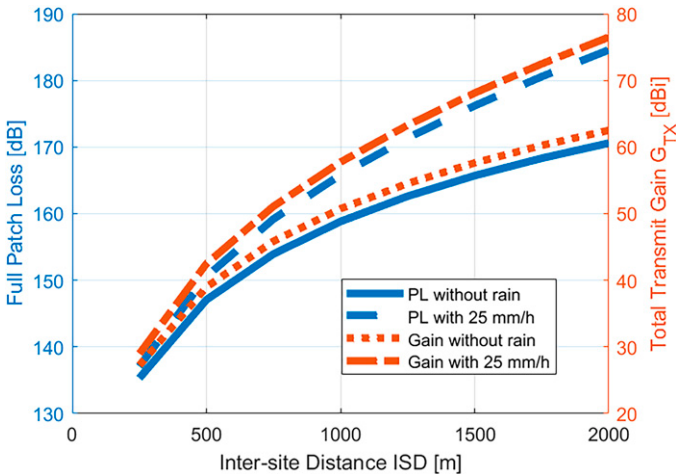


Fig. 6. Path loss and required transmit gain for different transmission distance ISD at 28 GHz.

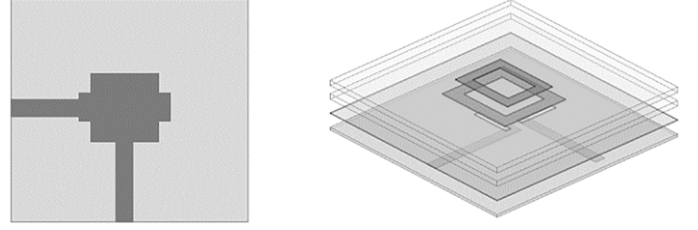


Fig. 7. Examples of a dual-band dual-polarized antenna.

Moreover, standard PCB technology based on a cost-effective substrate material Megtron6 is used for design and fabrication of the proposed antenna. This can lead to a reduction in the cost fabrication of 5G systems and products.

B. Antenna Design

In Fig. 8 we propose a dual-band dual-polarized antenna configuration for 5G mmWave operating at 28/38 GHz, which has a size of $5.4 \text{ mm} (\lambda_{28}/2) \times 5.4 \text{ mm} (\lambda_{28}/2)$ (see Fig. 8a). The antenna is designed on a multilayer PCB substrate. The stack-up (Fig. 8b) consists of two core Megtron6 R5775 ($\epsilon_r = 3.62$ and $\tan\delta = 0.006$) dielectric layers (h1 and h3), each has a thickness of 300 μm , and three prepreg Megtron6 R-5670 Type 3313 ($\epsilon_r = 3.55$ and $\tan\delta = 0.004$) layers (h2 and h4). Each prepreg layer has a thickness of about 102 μm . The stack-up also consists of five copper layers. Each copper layer is 35 μm thick. The proposed antenna configuration includes three stacked patches. The patch in the second metal layer is designed to resonate at 28 GHz, whereas for operations at 38 GHz the stacked patches consisting of a driven patch in the third copper layer and a parasitic patch in the first copper layer are used. The antenna is excited using aperture-coupled feedings, which consist of apertures slotted on the ground plane and microstrip feeding lines. The slots have an H-shape for better coupling from the transmission lines to the patches. To have the dual linear polarization (P1 and P2), two orthogonal microstrip lines and two slots are used to excite the antenna. Fig. 8c shows different layers as well important geometries of the proposed antenna.

As can be seen in the stack-up, the 28 GHz patch and 38 GHz driven patch are located in a superstrate. The effective length of the patches can be calculated using the following equation:

$$L_{\text{eff}} = \frac{c}{2f_r \sqrt{\epsilon_{b\text{-eff}}} \sqrt{\epsilon_{t\text{-eff}}}} \quad (6)$$

where c is the speed of light; f_r is the desired resonance frequency; and $\epsilon_{b\text{-eff}}$ and $\epsilon_{t\text{-eff}}$ are the effective permittivity of the top and bottom substrate, respectively.

The effective permittivity can be then calculated according to the following equation for $W/h > 1$:

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-0.5} \quad (7)$$

where h is the substrate thickness and W is the patch width. The patch width W is chosen based on the eq. (8).

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (8)$$

Table III
Overview of Dual-Band Dual-Polarized Antenna for mmWave Applications

References	Bandwidth of 3 GHz	Isolation between polarizations (dB)	Measured	Thickness of substrate (μm)	Lateral dimensions of single element	Gain
[19]	No	< -18	No	1,108	$3 \times 3 \text{ mm}$	7.7/9.4 dBi at 28/38 GHz
[20]	Yes	< -10	No	1,008	$2.75 \times 2.75 \text{ mm}$	8/9.5 dBi at 28/38 GHz
[21]	No	< -25	No	127	$2.7 \times 2.7 \text{ mm}$	6.7/7.5 dBi at 28/38 GHz
[22]	Yes	< -17	No	1,860	$3.5 \times 3.5 \text{ mm}$	6.5/5.8 dBi at 28/38 GHz
[23]	Yes	< -15	No	900	$3.8 \times 3.8 \text{ mm}$	7.1/6.4 dBi at 28/38 GHz
[24]	No	< -20	No	1,200	$9 \times 11.5 \text{ mm}$	7.5/8.5 dBi at 28/38 GHz
[25]	Yes	< -20	No	1,900	$1.84 \times 1.84 \text{ mm}$	6 dBi at 28/38 GHz
[26]	No	< -20	No	Not given	Not given	$> 6/4 \text{ dBi}$ at 28/38 GHz
Proposed antenna	Yes	< -20	Yes	1,200	$1.8 \times 1.8 \text{ mm}$	6/6.7 dBi at 28/38 GHz

From the calculated values of W , the effective permittivity is 3 and 3.1 for the bottom substrate and 3.2 and 2.9 for top substrate at 28 and 38 GHz, respectively. The calculated effective patch length is then 1.74 and 1.3 mm at the center frequencies

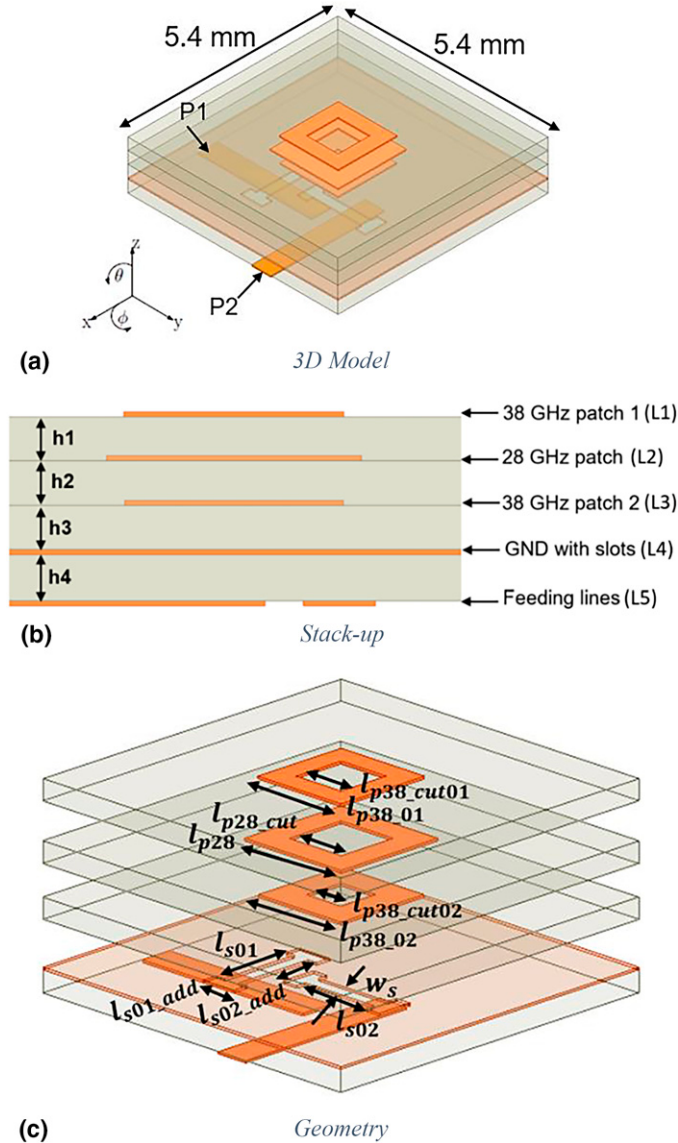


Fig. 8. Proposed dual-band dual-polarized patch antenna.

Table IV
Simulated Dimensions of the Proposed Antenna

Parameter	Values (mm)	Parameter	Values (mm)
l_{p38_01}	1.51	l_{s01}	1.25
l_{p38_cut01}	0.82	l_{s01_add}	0.55
l_{p38_02}	1.5	l_{s02}	1.25
l_{p38_cut02}	0.625	l_{s02_add}	0.55
l_{p28}	1.75	w_s	0.25
l_{p28_cut}	0.94	$h_{1 \rightarrow 4}$	0.3

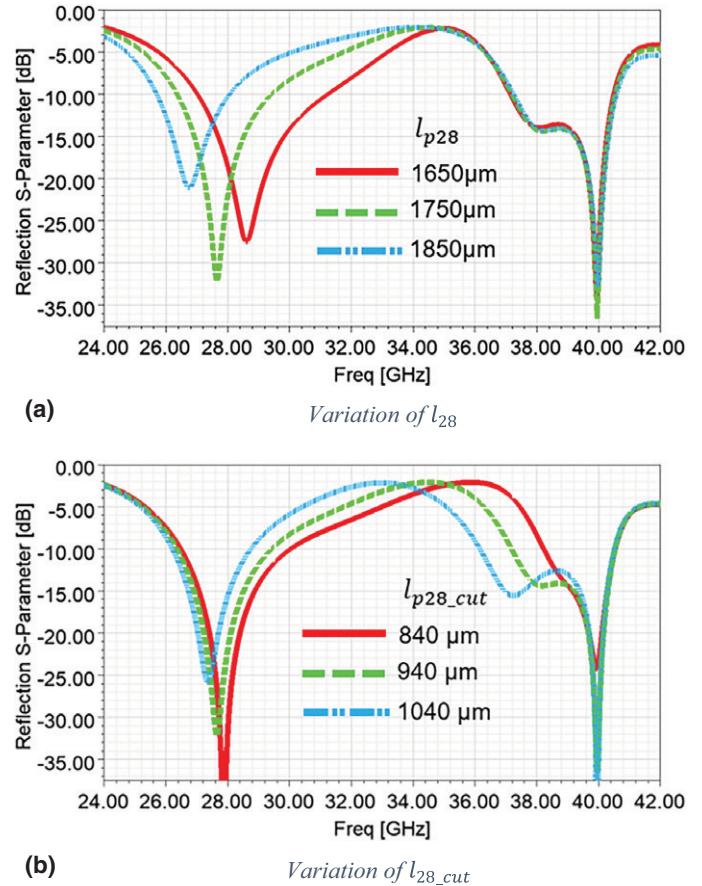


Fig. 9. Impact of inner and outer patch length of 28GHz antenna on return loss.

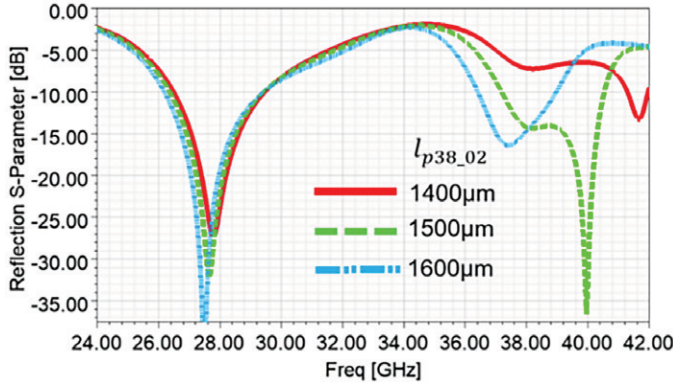
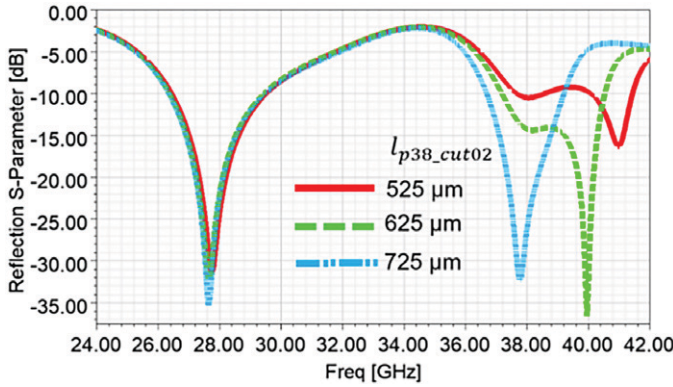
(a) Variation of l_{p38_02} (b) Variation of l_{p38_cut02}

Fig. 10. Impact of inner and outer patch length of 38 GHz bottom antenna.

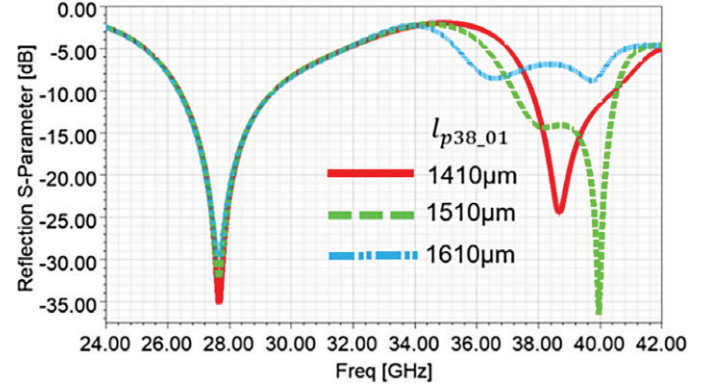
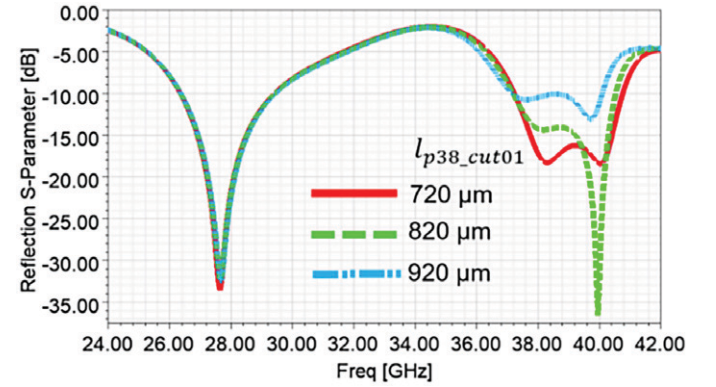
(a) Variation of l_{p38_01} (b) Variation of l_{p38_cut01}

Fig. 11. Impact of inner and outer patch length of 38 GHz top antenna.

28 and 38.5 GHz of the mmWave bands. The dimensions of the square rings inside the patches are chosen by a half of the effective patch length (0.87 mm for 28 GHz and 0.65 mm for 38.5 GHz). For generating the dual polarization characteristic, the patch width should be equal to the patch length L .

Taking the calculated values as initial values, the antenna was modeled and optimized using 3D Full-Wave Simulator ANSYS HFSS in the frequency range between 24 and 42 GHz. Wave ports are used to excite the antenna. The simulated dimensions of the proposed antennas are given in Table IV.

Since the proposed antenna consists of different patches locating in different substrate layers for resonating at 28 and 38.5 GHz, investigations of different design parameters are performed for better understanding the operation principle as well as impact of each parameter on the resonance frequency, impedance matching and bandwidth of the antennas. Fig. 9 shows return loss for various outer and inner lengths of 28 GHz patch l_{28} and l_{28_cut} . As l_{28} increases, the resonance frequency of the 28 GHz frequency band shifts to lower frequencies and there is no impact on the 38 GHz band. Increasing the inner patch length l_{28_cut} results slightly shift in lower frequencies and bandwidth reduction at 28 GHz. In contrast to this, the impedance bandwidth of the 38 GHz band increases significantly with bigger l_{28_cut} , since the lower resonance of the 38 GHz band from the parasitic patch in the top layer shifts to lower band due to better coupling from the driven patch

through bigger opening in the 28 GHz patch, whereas the higher resonance from the driven patch remains. In Fig. 10, return loss of different patch lengths l_{p38_02} and l_{p38_cut02} of the 39 GHz driven patch is shown. As l_{p38_02} and l_{p38_cut02} increase, the higher resonance from the driven patch shifts to lower band, whereas the lower resonance from the parasitic patch

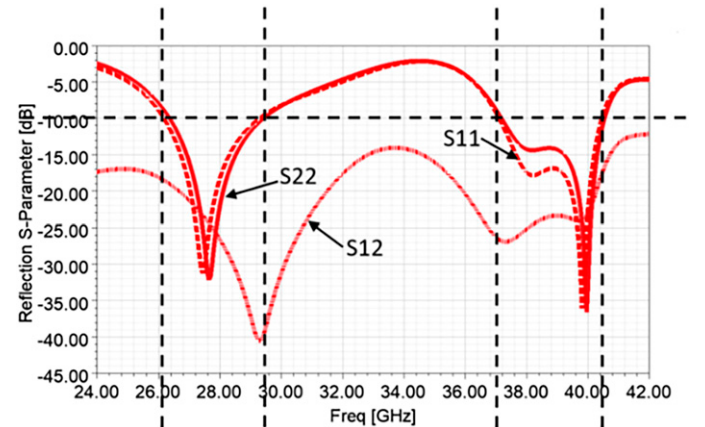


Fig. 12. Optimized simulated return loss and polarization coupling of the proposed dual-band dual-polarized antenna.

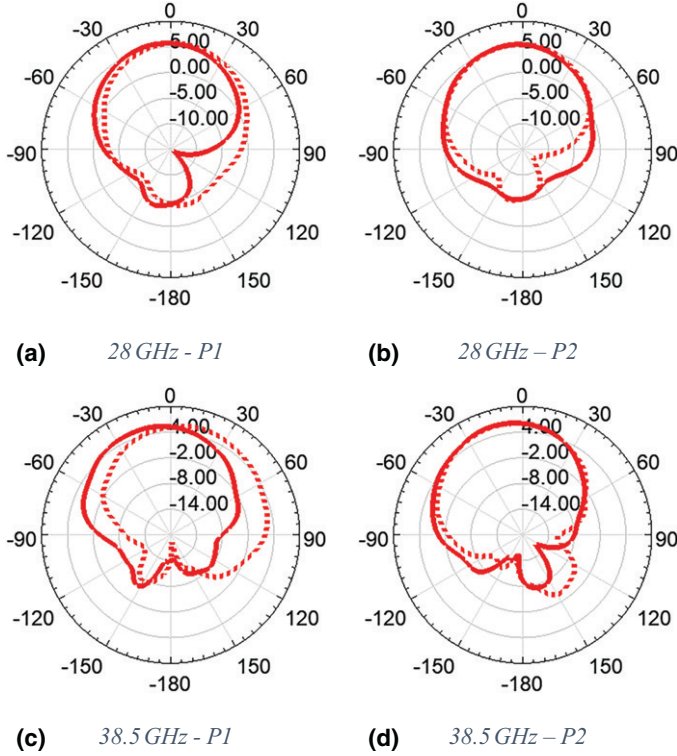


Fig. 13. Optimized simulated copolarization radiation patterns of the proposed dual-band dual-polarized antenna at 28 and 38.5 GHz: ZX-plane (solid line) and ZY-plane (dash line).

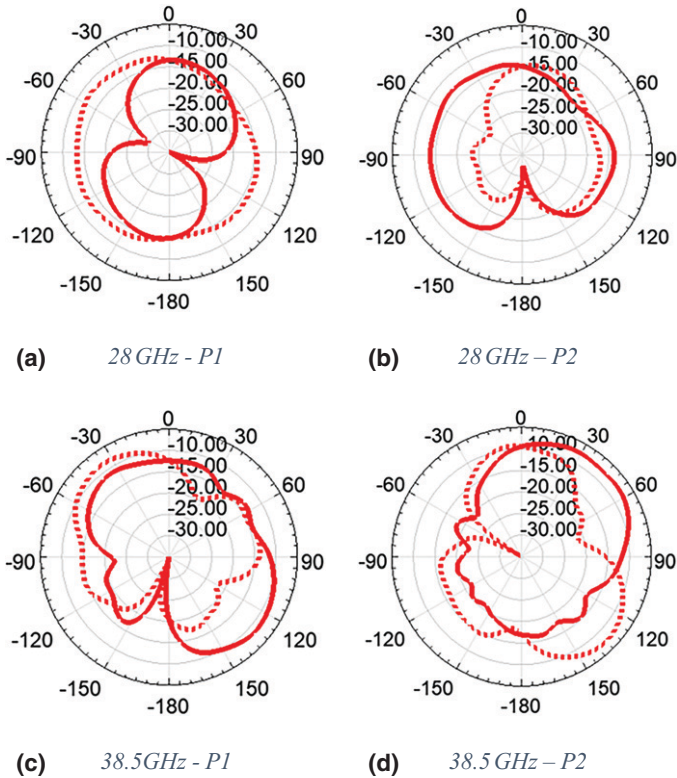


Fig. 14. Optimized simulated cross-polarization radiation patterns of the proposed dual-band dual-polarized antenna at 28 and 38.5 GHz: ZX-plane (solid line) and ZY-plane (dash line).

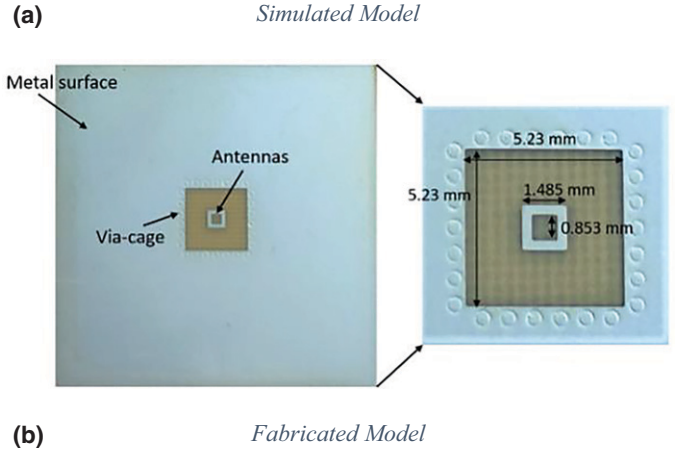
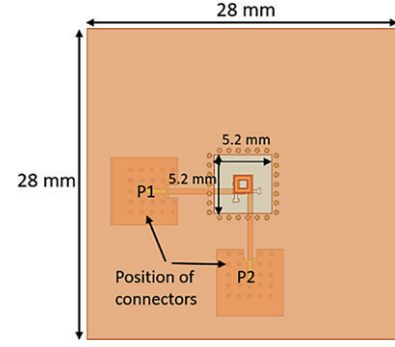


Fig. 15. Simulated and fabricated structure of the proposed dual-band dual-polarized antennas.

stays almost constantly. This leads to a strong reduction in impedance bandwidth at 38 GHz. Fig. 11 shows the impact of inner and outer patch length of the 38 GHz parasitic patch in the top layer. As can be seen, by increasing the outer patch length l_{38_01} , the resonance frequency from the parasitic patch shifts to lower band and the one from driven element remains. There is only slightly shift in the resonance from the parasitic patch, when the inner patch length l_{38_cut01} varies from 820 to 1,020 μm . However, the coupling between the driven and parasitic resonance decreases with bigger l_{38_cut01} and thus the impedance matching in the 38 GHz band is deteriorated.

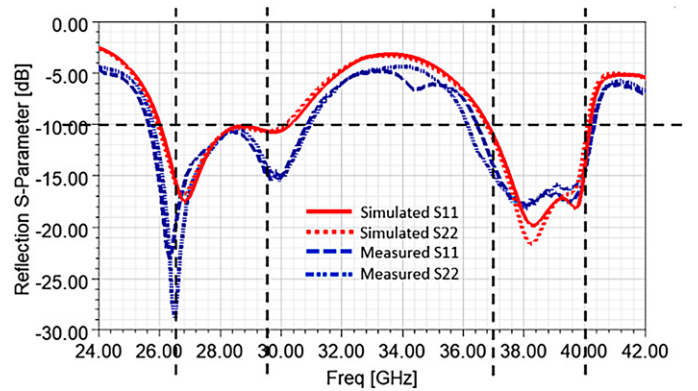


Fig. 16. Simulated and measured antenna return loss of the proposed dual-band dual-polarized antenna.

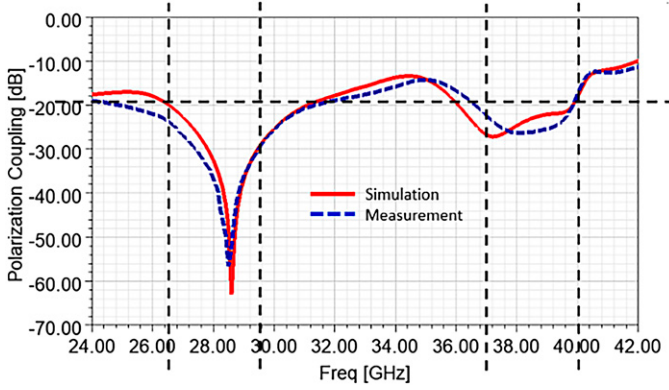


Fig. 17. Simulated and measured polarization coupling of the proposed dual-band dual-polarized antenna.

After the optimization process, the optimized simulated return losses for both polarizations and polarization coupling of the proposed antenna are shown in Fig. 12.

The results show an achieved impedance bandwidth of 3 GHz in the 28 GHz band and 3.3 GHz in the 38 GHz band for both polarization, which covers the 3 GHz bandwidths specified in the 5G NR n257 and n260 bands. In the achieved bandwidth, a coupling between two polarizations is lower than -20 dB in the 28 GHz band and -23 dB in the 38 GHz band. In Fig. 13, simulated radiation patterns in ZX- and ZY-plane at 28 and 38.5 GHz for both polarizations of the antenna are plotted. A maximum gain of 5.5 dBi at 28 GHz and 6 dBi at 38.5 GHz is obtained for both polarizations. The proposed antenna configuration has a maximum cross-polarization gain of -12 and -13 dBi at 28 GHz, -8.3 and -7.3 dBi at 38.5 GHz at polarization 1 and 2 (see Fig. 14). Simulated radiation efficiency is about 95% at 28 GHz and 92% at 38.5 GHz.

C. Antenna Measurement

For the measurement of return loss, polarization coupling and radiation pattern of the proposed dual-band dual-polarized antenna, coaxial connectors were used. To place the connectors on the antenna test board, the dimensions of the antenna substrate and ground plane were increased to about $2.5 \times 2.5 \lambda_{28}$. Bigger antenna board causes distortions in the antenna radiation patterns. To minimize these distortions, the proposed antenna is surrounded by a metal surface, which is short-circuited to the antenna ground plane by using a series of vias (see Fig. 15a). Compared with the stack-up in Fig. 8b, the fabricated stack-up includes two additional vias layers. The first

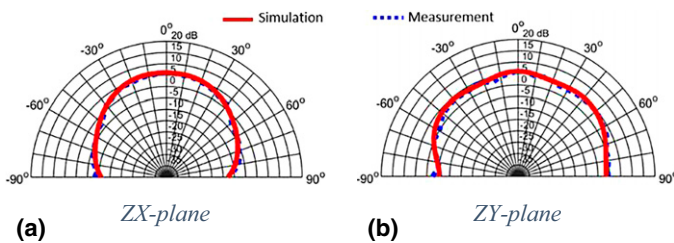


Fig. 18. Simulated and measured radiation pattern of polarization 1 of the proposed dual-band dual-polarized antenna at 28 GHz.

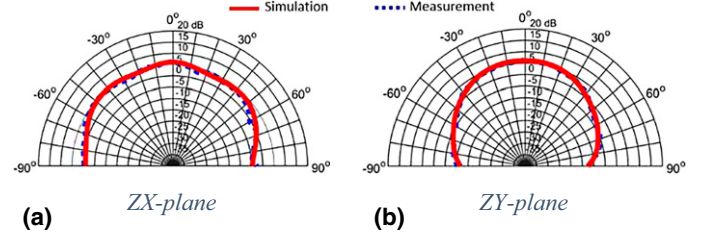


Fig. 19. Simulated and measured radiation pattern of polarization 2 of the proposed dual-band dual-polarized antenna at 28 GHz.

vias layer is used to connect the metal surface around the antenna in the top copper layer L1 to the antenna ground plane layer L4. The last vias layer between the antenna ground plane L4 and the last copper layer L5 serves as grounded vias for the connectors. The stack-up was fabricated with a plugged buried core (L1-L4). Also, the L1-L4 vias are filled with resin after the copper sleeves are built up. Blind vias were realized between L4 and L5. Fig. 15b shows a fabricated antenna structure.

The geometrical dimensions of the antennas were measured using a microscope and a maximum fabrication tolerance of approximately $30 \mu\text{m}$ was observed.

The return loss and radiation pattern of the proposed dual-band dual-polarized antenna were measured inside an anechoic antenna chamber. Fig. 16 shows very good correlation between simulation and measurement results for both polarizations.

Measured impedance bandwidths of approximately 5.3 and 4 GHz were obtained at 28 and 38 GHz bands, respectively. The simulated bandwidths are 4.3 and 3.4 GHz at 28 and 38 GHz bands. In Fig. 17 the measured coupling between two polarizations is plotted. In the achieved antenna bandwidth, the coupling is lower than -20 dB in the 28 and 38 GHz band.

The comparison between simulated and measured antenna radiation patterns at 28 and 38.5 GHz for two polarizations is shown in Fig. 18-21.

The measured peak gain of approximately 6 dBi at 28 GHz band and 6.7 dBi at 38 GHz band for polarization 1 and 2 is achieved, compared with the simulated 6.1 dBi at 28 GHz band and 6.8 dBi at 38 GHz band.

Compared with the other dual-band dual-polarized antenna configurations in published literature, our antenna configuration meets the performance requirement with very wide bandwidth and high gain, as can be seen in Table III. Hence, this antenna can cover the entire specified 3 GHz bandwidth in the 28 and 38 GHz frequency bands. In addition, with its smaller dimensions, a high degree of miniaturization can be achieved.

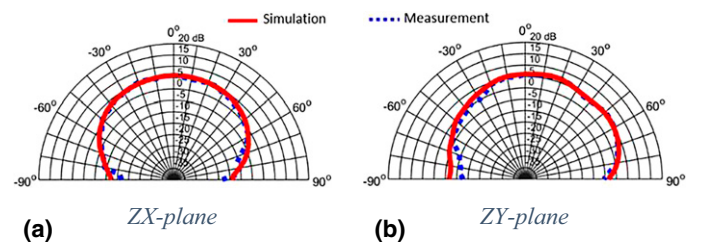


Fig. 20. Simulated and measured radiation pattern of polarization 1 of the proposed dual-band dual-polarized antenna at 38.5 GHz.

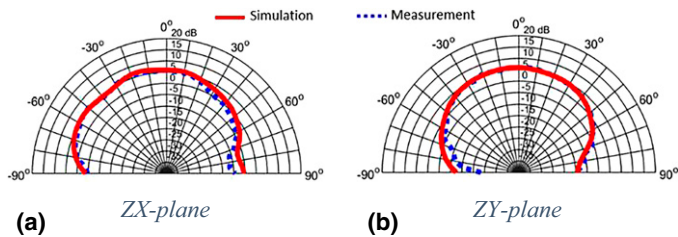


Fig. 21. Simulated and measured radiation pattern of polarization 2 of the proposed dual-band dual-polarized antenna at 38.5 GHz.

CONCLUSION

In this contribution, we presented a systematic approach for the development of application-specific antennas for 5G mmWave BST. First, an in-depth analysis of 5G mmWave BST considering the required antenna gain and antenna elements to address different EIRP requirements is presented. This is followed by an evaluation of the realistic impact of different factors which affect mmWave communication, namely output power of power amplifiers, antenna gain, losses and weather condition (rain), on achievable transmission ranges between base station and terminals, considering the link budget analysis for an UMa with the NLOS transmission, as an example. The investigation results show that the path loss increases with the ISD between the base station and the user terminal. To improve the transmission distance/data rate, high antenna gain is required. Especially, for outdoor communication, the achievable range with the same antenna gain could be reduced by bad weather conditions such as rain or fog. Finally, based on a comparative analysis of published dual-band dual-polarized 5G mmWave antennas, we propose a novel configuration of a dual-band dual-polarized antenna for 5G mmWave base station applications, which overcomes the limitations of other antennas in published literature. In addition, the impacts of different antenna parameters on the antenna resonance frequency, impedance matching and bandwidth are investigated and analyzed. Our proposed antenna covers the specified 3 GHz bandwidths in the 5G NR n257 and n260 bands, reaches about 6 and 6.7 dBi, respectively, in these bands, exhibits at least 20 dB isolation between the polarizations and has dimensions of $1.8 \times 1.8 \times 1.2$ mm. Excellent correlation is obtained between measurement and simulation results. This demonstrates that our proposed dual-band dual-polarized antenna is very suitable for the development of AiP modules for 5G mmWave BST.

REFERENCES

- [1] I. Ndip and K. Lang, "Roles and requirements of electronic packaging in 5G," 2018 7th Electronic System-Integration Technology Conference (ESTC), pp. 1-5, Dresden, Germany, 18-21 September 2018.
- [2] "5G's Impact on RF Front-End for Telecom Infrastructure 2021," Report [Online]. www.yole.fr, 2021.
- [3] G. Guo, L. Wu, Y. Zhang, and J. Mao, "Stacked patch array in LTCC for 28 GHz antenna-in-package applications," 2017 IEEE Electrical Design of Advanced Packaging and Systems Symposium (EDAPS), pp. 1-3, Haining, China, 14-16 December 2017.
- [4] K. Keum and J. Choi, "A 28 GHz 4×4 U-slot patch array antenna for mm-wave communication," 2018 International Symposium on Antennas and Propagation (ISAP), pp. 1-2, Busan, South Korea, 23-26 October 2018.
- [5] T.H. Le, I. Ndip, O. Schwanitz, S. Kosmider, K.S. Murugesan, U. Maass and M. Schneider-Ramelow, "Compact wideband antenna-in-package based on PCB technology for 39 GHz 5G mmWave applications," 2022

- 16th European Conference on Antennas and Propagation (EuCAP), pp. 1-4, Madrid, Spain, 27 March - 01 April 2022.
- [6] M. Nosrati and N. Tavassolian, "A single feed dual-band, linearly/circularly polarized cross-slot millimeter-wave antenna for future 5G networks," 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 2467-2468, San Diego, CA, 09-14 July 2017.
- [7] W. Ahmad and W.T. Khan, "Small form factor dual band (28/38 GHz) PIFA antenna for 5G applications," 2017 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM), pp. 21-24, Nagoya, Japan, 19-21 March 2017.
- [8] N. Ashraf, O. Haraz, M.A. Ashraf, and S. Alshebeili, "28/38-GHz dual-band millimeter wave SIW array antenna with EBG structures for 5G applications," 2015 International Conference on Information and Communication Technology Research (ICTRC), pp. 5-8, Abu Dhabi, United Arab Emirates, 17-19 May 2015.
- [9] O. Haraz, M.M.M. Ali, A. Elboushi, and A. Sebak, "Four-element dual-band printed slot antenna array for the future 5G mobile communication networks," 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 1-2, Vancouver, BC, Canada, 19-24 July 2015.
- [10] H. Aliakbari, A. Abdipour, R. Mirzavand, A. Costanzo, and P. Mousavi, "A single feed dual-band circularly polarized millimeter-wave antenna for 5G communication," 2016 10th European Conference on Antennas and Propagation (EuCAP), pp. 1-5, Davos, Switzerland, 10-15 April 2016.
- [11] J.-K. Du, K. So, Y. Ra, S.-Y. Jung, J. Kim, S.Y. Kim, S. Woo, H.-T. Kim, Y.-C. Ho, and W. Paik, "Dual-polarized patch array antenna package for 5G communication systems," 2017 11th European Conference on Antennas and Propagation (EuCAP), pp. 3493-3496, Paris, France, 19-24 March 2017.
- [12] E.A. Abbas, A.T. Mobashsher, and A. Abbosh, "Polarization reconfigurable antenna for 5G cellular networks operating at millimeter waves," 2017 IEEE Asia Pacific Microwave Conference (APMC), pp. 772-774, Kuala Lumpur, Malaysia, 13-16 November 2017.
- [13] "5G Smallcells 2021-2031 Technology Markets Forecast," [Online]. <https://www.idtechex.com/de/research-report/5g-small-cells-2021-2031-technologies-markets-forecast/825>.
- [14] "RF Front-End for Mobile 2023," Report [Online]. www.yolegroup.com, 2023.
- [15] "Telefonica, Ericsson and Qualcomm launch first commercial mobile 5G mmWave network in Spain at MWC 2023," Barcelona [Online]. <https://www.ericsson.com/en/pressreleases/3/2023/telefonica-ericsson-and-qualcomm-launch-first-commercial-mobile-5g-mmwave-network-in-spain-at-mwc-2023-barcelona>, 2023.
- [16] P.M. Asbeck, N. Rostomyan, M. Özen, B. Rabet, and J.A. Jayamon, "Power amplifiers for mm-Wave 5G applications: technology comparisons and CMOS-SOI demonstration circuits," IEEE Transactions on Microwave Theory and Techniques, Vol. 67, No. 7, pp. 3099-3109, 2019.
- [17] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, "Study on channel model for frequencies from 0.5 to 100 GHz (Release 16), 3GPP TR 38.901 V16.1.0," 2019.
- [18] M. Marcus and B. Pattan, "Millimeter wave propagation: spectrum management implications," IEEE Microwave Magazine, Vol. 6, No. 2, pp. 54-62, 2005.
- [19] S.S. Haider, F.A. Tahir, H.T. Chattha, and Q.H. Abbasi, "Compact polarization diversity antenna for 28/38 GHz bands," 2018 18th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEN), pp. 1-2, Waterloo, ON, Canada, 19-22 August 2018.
- [20] S.S. Haider, M.R. Wali, F.A. Tahir, and M.U. Khan, "A fractal dual-band polarization diversity antenna for 5G applications," 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 763-764, San Diego, CA, 09-14 July 2017.
- [21] S. Lee, S. Kim, and J. Choi, "Dual-band dual-polarized proximity fed patch antenna for 28 GHz/39 GHz 5G millimeter-wave communications," 2019 13th European Conference on Antennas and Propagation (EuCAP), pp. 1-5, Krakow, Poland, 31 March - 05 April 2019.
- [22] Y. He, M. Rao, Y. Liu, G. Jing, M. Xi, and L. Zhao, "28/39-GHz dual-band dual-polarized millimeter wave stacked patch antenna array for 5G applications," 2020 International Workshop on Antenna Technology (iWAT), pp. 1-4, Bucharest, Romania, 25-28 February 2020.
- [23] M. Stanley, Y. Huang, H. Wang, H. Zhou, A. Alieldin, S. Joseph, C. Song and T. Jia, "A dual-band dual-polarised stacked patch antenna for 28 GHz and 39 GHz 5G millimetre-wave communication," 2019 13th European Conference on Antennas and Propagation (EuCAP), pp. 1-4, Krakow, Poland, 31 March - 05 April 2019.

- [24] H. Lin and Y. Lin, "A dual-band and dual-polarized aperture antenna for 5G millimeter-wave applications," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, pp. 423-424, Atlanta, GA, 07-12 July 2019.
- [25] Z.Y. Siddiqui, M. Sonkki, J. Chen, M. Berg, M. Leinonen, and A. Parssinen, "Dual-band dual-polarized antenna for mm-wave 5G base station antenna array," 2020 14th European Conference on Antennas and Propagation (EuCAP), pp. 1-4, Copenhagen, Denmark, 15-20 March 2020.
- [26] C. Chu, J. Zhu, S. Liao, A. Zhu, and Q. Xue, "28/38 GHz dual-band dual-polarized highly isolated antenna for 5G phased array applications," 2019 IEEE MTT-S International Wireless Symposium (IWS), pp. 1-3, Guangzhou, China, 19-22 May 2019.