Research Article

Demonstration of Millimeter Wave 5G Setup Employing High-Gain Vivaldi Array

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We present a 4×4 slot-coupled Vivaldi antenna (SCVA) array unit cell, which offers wide bandwidth and high gain (~ 23 dBi) at the millimeter wave (mmW) frequencies of 28 GHz and 38 GHz. A single SCVA element is first presented, which has a bandwidth of 25–40 GHz with an average gain of ~ 13 dBi at the frequencies of interest. This antenna element is then used to design a 1×4 linear SCVA array matched to a 50Ω impedance via a modified Wilkinson power divider (WPD). Next, the 1×4 linear array is used to construct a 4×4 antenna array unit cell. The proposed 4×4 antenna array unit cell is fabricated, and the characteristics of its elements (i.e., the single SCVA, 1×4 linear array, and WPD) are thoroughly investigated. Further, the 4×4 array is tested for signal reception of various digital modulation formats at lab environment using high-speed digital signal oscilloscope. In particular, a 2.5 Gbps data rate is successfully transmitted achieving receiver sensitivity of -50 dBm at 2×10^{-3} bit error rate (BER) for 32 quadrature amplitude modulation (QAM) with a system baud rate of 500 MHz. The wide bandwidth and high gain along with the excellent performance of the proposed 4×4 antenna array unit cell makes it an excellent candidate for future 5G wireless communication applications.

1. Introduction

Rapid development of wireless networking techniques in the last decade have introduced a bundle of wireless services that are being utilized by various smart devices. These devices consume massive bandwidth and are still hungry for more, which in turn increase the data traffic on the wireless networks [1]. In order to satisfy the ever-growing demands of consumers and wireless market, the millimeter wave (mmW) band, with its huge bandwidth compared to that of the currently utilized bands for wireless communications, seems to provide a promising solution. The mmW band has attracted a lot of attention over the last years from both the scientific research community and industry alike, as it is acknowledged for being a key technology in the development and implementation of the fifth generation (5G) mobile

communication systems [2–4]. The standardization of 5G communication frequency bands and networking protocols, along with the development of commercial hardware, is underway and expected to be ready by early 2020 [5].

One key enabling technique in 5G communication systems is the use of mmW antenna arrays for signal transmission and reception. The design of antenna arrays of wideband and high-gain characteristics in the mmW band is a challenging task. Few attempts have been reported in the literature considering the design of mmW antenna arrays at 28 GHz and/or 38 GHz. In [6], a 5G-phased array mobile communication is considered, where the array consists of ten-slot loop antennas. The antenna array is designed using FR-4 substrate with reported gain around 13 dBi, covering the band from 27 GHz to 29 GHz. Because of the utilized substrate, this design intrinsically exhibits high losses, which are

TABLE 1: Characteristic comparison of various Vivaldi antenna designs.

Single element						Arrays		
Ref.	Frequency	Bandwidth (GHz)	Gain (dBi)	Dimensions (mm)	Bandwidth (GHz)	Gain (dBi)	Number of elements	Dimensions (mm)
[17]	32 GHz	24.5–40	7	$14 \times 8 \times 0.508$	28–38	15	1×8	$60 \times 30.2 \times 0.508$
[18]	28 GHz	27.4–28.6	5.39	$17.25 \times 5 \times 0.8$	27.4–28.6	12	1×8	$130 \times 60 \times 0.8$
[19]	28 GHz	26–31	4	$15 \times 5 \times 0.4$	26–31	16	1×8	$15 \times 5 \times 0.8$
[20]	28 GHz	25–40	13	$59 \times 8 \times 0.508$	—	—	—	—
[21]	28 GHz	10–40	12	$79.9 \times 24 \times 0.254$	—	—	—	—
Proposed	28/38 GHz	25–40	13	$73.4 \times 19.3 \times 0.203$	25–40	16	1×4	$135 \times 97.5 \times 0.203$

FIGURE 1: (a) Geometric design (top and bottom) of the proposed single-element SCVA. (b) Realized prototype of SCVA (top view).

more pronounced at the mmW band. In [7], authors used a planar antipodal fermi tapered slot array antenna in the frequency band of 27–32 GHz in order to reduce mutual coupling among two antenna elements. The design has the features of having wide bandwidth and low isolation and side lobe levels with an average gain of 15 dBi. All this was achieved by introducing metamaterial corrugations on the edge of the tapered slot design. In [8], three patch antenna array designs were realized for the 28 GHz band. Two among the three patch arrays were designed on a printed circuit board (PCB) material while one array design was made on

low temperature co-fired ceramic (LTCC) to increase the gain and achieve wide bandwidth. The patch array designed on PCB offered a gain of 13 dBi with a single resonance at 28 GHz while the LTCC material array (2×2) achieved a gain of 10 dBi with a wide bandwidth of 10.3% (26–29 GHz). In [9], the authors utilized the substrate integrated waveguide (SIW) technology to design a low-cost and high-gain antenna array for 5G communication. Slotted antennas in the shape of rectangles are designed on a substrate with permittivity of 2.2. The arrays of slots are placed in such a way that the E-field distribution can be controlled in order to get higher

FIGURE 2: (a) Stub angle optimization. (b) Simulation and measured S_{11} results of the proposed SCVA.

gain. The authors proposed a 3×3 element antenna array, which covers a bandwidth ranging from 28 to 36 GHz and has a gain of 13.8 dBi with 92% efficiency. In [10], the authors used a dielectric resonator antenna (DRA) array to achieve high gain at 28 GHz band. A simple rectangular DRA array of 1×4 linear elements is designed and excited via various microstrip feeding techniques. The linear array of 1×4 DRA elements achieves an impedance bandwidth of 2.1 GHz with a gain of 14 dBi.

All the aforementioned 5G designs are either achieving wider bandwidth or having higher gain, with relatively complex design. In this paper, we propose an array design for 5G communications by using Vivaldi antenna, which can cope with both requirements effectively. Vivaldi antenna is a tapered slot-type antenna, whose design is simple and offers light weight, compact size, and minimal cost of realization [11]. Vivaldi antenna has been extensively studied in literature with various design improvements [12–16].

For the problem at hand, we present a wide bandwidth and high-gain antenna array to operate over the standard 28 GHz and 38 GHz bands for 5G wireless communication systems. Initially, we propose and design a slot-coupled Vivaldi antenna (SCVA). Next, we design, fabricate, and characterize a complete 4×4 SCVA array unit cell, operating at the targeted mmW frequencies. The proposed antennas are designed using the low-loss tangent material RO4003 substrate and enjoys a gain > 20 dBi and a wide bandwidth from 25 to 40 GHz covering frequencies of interest at 28 GHz and 38 GHz. The performance of the proposed array is further evaluated with respect to reception of various wirelessly transmitted standard digital modulation schemes. The performance is presented in terms of signal constellation diagrams and bit error rate (BER) values at various input power levels. Characteristic comparison of our design with various Vivaldi antennas is listed in Table 1. It can be seen in Table 1 that our proposed Vivaldi designs (single element and array) offer comparable and even better performance in terms of gain, dimensions, and bandwidth at the standard 5G communication bands.

TABLE 2: Optimized parameters of the proposed SCVA [24].

Parameters	Value (mm)
Substrate length L_{sub}	73.4
Substrate width W_{sub}	19.3
Feed width W_f	0.47
Stripline length	9.43
Coupler length	2.1
Stub radius	1.56
Stub angle, α	80°
Via diameter, D_{vias}	0.6
Spacing among vias, s	4.8
Circular slot vias spacing, C_{sd}	1.4
Start gap of circular slot, g	13.4
Flare opening, H_f	15.16
Circular slot diameter, D_{cs}	2

2. Slot-Coupled Vivaldi Antenna (SCVA)

2.1. The Single Antenna Element. The bandwidth and gain of a single antenna element play an important role in defining the characteristics of the corresponding antenna array system. Various types of antennas offering wide bandwidth and high gain have been discussed in literature, including the dielectric rod antenna, spiral antenna, horn antenna, and log periodic antenna [22–25]. Perhaps the most popular type is Vivaldi antenna, also known as the tapered slot antenna (TSA) [26]. This antenna has a flared slot line aperture similar to the flared horn waveguide, which is the basis for its attractive features such as the wide bandwidth, low value of VSWR (< 2), and high gain for large arrays. Moreover, Vivaldi antenna is mostly printed on substrates that are fed via stripline or microstrip technology, which makes it easily integrable with other wireless components and devices.

In this study, we first start with the design of SCVA. Here, we make use of the theoretical design results initially reported by the authors in [27]. For coherency of presentation, we briefly summarize these results but also add new results

FIGURE 3: 3D radiation pattern of the proposed antenna at (a) 28 GHz with a gain of 12.9 dBi and (b) 38 GHz with a gain of 13.59 dBi. Simulated and measured E-plane (left side) and H-plane (right side) 2D radiation patterns at (c) 28 GHz and (d) 38 GHz.

pertaining to the fabricated prototype. Configuration of the proposed SCVA is shown in Figure 1(a), while the realized structure is shown in Figure 1(b). The SCVA is printed on the top and bottom side of Rogers RO4003 substrate having permittivity of 3.55, loss tangent of 0.0027, and thickness of 0.203 mm. The feed line conductor matched to a 50Ω impedance is on the back side of the substrate. The feed line follows a stripline-to-microstrip slot conversion using a radial stub. This technique provides a wide impedance bandwidth. The radial stub was varied at different angles (0° – 90°) with the optimum results presented in Figure 2(a). The exponential flare conductors of Vivaldi antenna are attached with a circular slot on the top side of the substrate. Both of them play a vital role and are responsible for the propagation of the waves in an end-fire directional plane. The exponential flare has contoured holes or vias along the tapered edges of the metalized conductors. These contours control and limit the radiation losses introduced in the SCVA [9]. The exponential profile of the antenna is characterized by the opening rate R , which is governed by the well-defined relations developed in [28]. The final optimized parameters for the proposed single-element SCVA are shown in Table 2.

Figure 2(b) presents the measured reflection coefficient S_{11} of the single-element SCVA. The proposed antenna exhibits good impedance matching below -10 dB over a wide bandwidth from 23 to 47 GHz. It also covers the 5G bands of interest, that is, 28 GHz and 38 GHz. The normalized gain of

FIGURE 4: Geometric design of the single-section-modified WPD.

TABLE 3: Optimized parameters of the single-section-modified Wilkinson power divider with ports matched to 50Ω impedance.

Parameters	Value (mm)
L_1	0.7
L_2	0.3
R_L	1.3
R_w	0.7
W_o	0.39
W_1	0.4
W_2	0.2
Stub	0.1

FIGURE 5: (a) Geometric design and dimensions of M3WPD. (b) Realized prototype of the M3WPD.

3D radiation pattern and measured 2D polar plots are shown in Figures 3(a) and 3(b) for the proposed frequencies of 28 GHz and 38 GHz. It can be observed from the 3D figure that the gain of the antenna is 12.9 dBi and 13.5 dBi in the end-fire direction, according to the 2D E-plane and H-plane polar plots of radiation pattern. For 28 GHz frequency, the E-plane has a side lobe level of -10.4 dB and angular beam width of 27.8° while the H-plane has a side lobe level of -10.5 dB and angular beam width of 30.8° . Similarly, at 38 GHz, the E-plane has a side lobe level of -7.7 dB and angular beam width of 33.9° while the H-plane has a side lobe level of -9.3 dB and angular beam width of 23.3° .

2.2. The Feed Network. The single-element SCVA is used to construct a higher gain 1×4 linear array. This array is fed with a corporate feed network. Here, we consider Wilkinson power divider (WPD), which can reasonably deliver maximum power to the radiating elements of the array, offer good isolation among the ports, and provide wide bandwidth characteristics [29]. Note that adding cascaded sections to WPD's output ports or using PCB multilayer technology increases the bandwidth of WPD at the expense of increasing circuit dimensions, which in turn, presents poor insertion loss [30, 31]. For size compactness, this work considers the stepped impedance open circuit radial stub technology, where a modified three-section Wilkinson power divider (M3WPD) is used in the design of 1×4 linear array [32]. Figure 4 shows the design of a single section of the M3WPD, which contains a small square stub matched to each of its branch lines. A 100Ω thick film resistor, with part number 0402 produced by Vishay electronics, is placed at the output ports (port-2 and port-3) to isolate the power delivered to these two ports by the input port (port-1). The optimized parameters for the single section WPD are presented in Table 3.

Figure 5 shows the geometric dimensions and fabricated M3WPD, where Rogers RO4003 is again used as a substrate

in both simulation and fabrication. The performance characteristics of fabricated M3WPD are measured using Agilent Technologies network analyzer N5227A that is operational from 10 MHz to 67 GHz. The simulated and measured results are shown in Figure 6, where we observe that reflection coefficient S_{11} through S_{55} is below -10 dB over a wide range of mmW spectrum covering the bands of interest at 28 GHz and 38 GHz. Figure 6(a) shows simulated results of reflection coefficient from port-1 to port-5. Figure 6(b), on the other hand, shows the insertion loss and mutual coupling among the ports. The transmission coefficients with respect to port 1, that is, S_{12} , S_{13} , S_{14} , and S_{15} , have values around -7 dB at 28 GHz and 38 GHz. Theoretically, the measured transmission coefficient values fall in the range of -6 dB up to -7 dB . This condition is well satisfied at the 28 GHz frequency band. However, due to fabrication tolerances and manual insertion of discrete components that might become very critical at higher frequencies, we have found additional losses up to 4 dB as can be seen in Figure 6(d) at 38 GHz. The mutual coupling among the output ports, specifically for the neighboring ports, should be as minimum as possible. We have found from the S-parameter measurements that S_{23} , S_{34} , and S_{45} (presenting mutual coupling between ports 2-3, ports 3-4, and ports 4-5, resp.) are well below -15 dB over the desired bandwidths (Figure 6(d)). By virtue of the measurement results, we observe that the M3WPD offers good isolation among ports and has wide bandwidth, which makes it a good feeding network for the 1×4 Vivaldi antenna array.

2.3. The 1×4 Linear Vivaldi Array. The optimized single-element SCVA and optimized M3WPD feeding network are integrated together to construct a 1×4 linear array. Antenna arrays can have higher gain and directivity with narrower beam width compared to single antenna elements. In general, the larger the number of individual antenna elements is, the higher the gain and the narrower the beam width are [33, 34].

FIGURE 6: Simulated results of the 1×4 WPD (a) return loss (S_{11}) and (b) insertion loss and isolation among ports. Measured results of the 1×4 WPD (c) reflection coefficients and (d) insertion loss and isolation among ports.

Figure 7 shows the geometric design of the antenna array, while Figure 8 shows the realized prototype. The original conductor or radiating element on the top side has a dimension of $L_c \times W_c$ while the substrate has a dimension of $L_s \times W_s$. The extra extension G_x (25 mm) in the design achieves a small increase in gain (around 0.5 dBi) and also assists in packaging the 4×4 unit cell in a transparent box, as will be discussed in the next section. The backside of the substrate has the M3WPD. The optimized dimensions of the linear array are presented in Table 4.

Figure 9 shows the simulated and measured S-parameters and gain of the proposed 1×4 linear Vivaldi antenna array. The antenna array is resonating in the required mmW

spectrum, covering a wide range from 25 to 40 GHz. Also, it has a maximum realized gain, in the principle E-plane, above 15 dBi over a flat bandwidth range. The normalized 2D polar plots of the measured radiation pattern at the center frequencies of 28 GHz and 38 GHz are shown in Figure 10. The 3D radiation pattern of the antenna array is shown in Figure 11. Referring to the figure, the array is highly directional with a gain of more than 15 dBi in the end-fire direction. The E-plane and H-plane responses of the array are observed from the 2D polar plots. For the frequency of 28 GHz, the E-plane has a side lobe level of -8.8 dB and an angular beam width of 6.7° , while the H-plane offers a side lobe level of -9.6 dB and angular beam

FIGURE 7: Geometric design of the 1×4 linear Vivaldi array antenna. (a) Top plane view and (b) back plane view.

FIGURE 8: Realized prototype of the 1×4 linear Vivaldi array integrated with WPD acting as feed network. (a) Top plane view and (b) back plane view.

TABLE 4: Optimized parameters of the 1×4 linear Vivaldi antenna array.

Parameters	Value (mm)
L_c	99
L_s	135
W_c	77
W_s	97.5
G_w	11.4
G_L	13
G_x	25
d_1	38.6
d_2	19.3

width of 29.1° . Similarly, for the 38 GHz frequency, the E-plane has a side lobe level of -8.4 dB and an angular beam width of 5° , while the H-plane offers a side lobe level of -8.2 dB and an angular beam width of 33.1° . The beam width is quite narrow in the E-plane as compared to the H-plane.

3. 4×4 mmW Antenna Array Unit Cell

3.1. S-Parameters and Mutual Coupling. The previously designed and experimentally verified 1×4 linear Vivaldi

FIGURE 9: Simulated and measured reflection coefficient S_{11} of proposed 1×4 linear array.

antenna array is used to construct a 4×4 antenna array unit cell inside an acrylic portable box. Figure 12(a) shows the layout of placement of arrays, while Figure 12(b) shows the final prototype. The CST MWS [35] array synthesis tool is used to calculate the radiation performance of the cell array. At the optimum distance (D_{space}) of 14 mm, the unit

FIGURE 10: Measured Co-pol radiation patterns of the 1×4 linear Vivaldi antenna array. (a) E-plane 28 GHz. (b) H-plane 28 GHz. (c) E-plane 38 GHz. (d) H-plane 38 GHz.

cell achieves a high gain of 22.4 dBi and 23.5 dBi at 28 GHz and 38 GHz, respectively. Figure 13 shows the 3D radiation pattern of the 4×4 mmW array unit cell at the frequencies of interest.

Figure 14 shows the measured mutual coupling between the different array ports. These measurements are performed before integrating the M3WPD with the array. It can be seen from the measured results of Figure 14 that the reflection coefficients of the individual ports S_{11} , S_{22} , S_{33} , and S_{44} have resonance below -10 dB at both the frequencies of interest. Also, the mutual coupling among ports, that is, S_{12} , S_{13} , S_{14} , and S_{23} is well below -20 dB. Figure 15, on the other hand, shows the return loss S_{11} after integrating the M3WPD with the 4×4 array. It can be observed from

the figure that the antenna radiates well below -10 dB over wide impedance bandwidths in the range from 25 to 40 GHz.

3.2. Array Performance in Wireless Communication. For further performance evaluation of the developed 4×4 array, an experimental setup is made for the transmission and reception of standard digital modulation formats over a wireless link. The block diagram of the setup is shown in Figure 16. At the transmission end, an arbitrary waveform generator (AWG), model number M8190, from Keysight with a sampling rate of 12 GSa/s is used to generate the baseband I- and Q-modulated signals with a system baud rate of 500 MHz. A MATLAB open source kit, called Keysight IQ

FIGURE 11: 3D gain of the proposed 1×4 linear Vivaldi antenna array at 28 GHz and 38 GHz.

FIGURE 12: (a) Layout of acrylic box for placement of four 1×4 antenna arrays. (b) Prototype of the 4×4 antenna array unit cell.

Tools, is used to implement the modulation techniques considered in this work. The baseband I/Q signals are sent through RF coaxial cables to the Keysight vector signal generator (VSG), model number E8267D, which works as an upconverter. Note that PSG applies a carrier offset to set the carrier frequency to the desired value. Moreover, it allows variation in the output power levels of transmitted signals from below -100 dBm up to 27 dBm. For a given fixed distance between the transmitting and receiving antennas, these features of PSG facilitate studying the array performance for the reception of different modulation schemes against variable-transmitted signals' strengths. In this setup, the RF output of PSG is transmitted using a horn antenna with a gain of 25 dBi. The horn antenna is the product of NSI-MI Company, with a bandwidth of 26.5 – 40 GHz. The distance between the transmitting and receiving antennas is kept

constant at 1.5 m. For this experimental setting at 28 GHz, this distance is in the far field and aligns with the range of distances previously considered in the literature [36, 37].

At the receiver side, the unit cell receives the transmitted modulation and displays the result on the digital storage oscilloscope of 80 GSa/s (Keysight DSO-X 93204A). The received signal is demodulated using the Keysight vector signal analyzer (VSA). Figure 17 shows the experimental results in the form of estimated BER for different modulation schemes versus transmitted/received power. The BER is inferred from the measured error vector magnitude (EVM). For a wireless distance of 1.5 m, we have a minimum receiver sensitivity of -53 dBm, -50.7 dBm, and -50 dBm for 16 QAM, 32 QAM, and OFDM-16 QAM, respectively, with BER below the forward error correction (FEC) limit. Also, a maximum successful wireless transmission of 2.5 Gbps data

FIGURE 13: 3D radiation pattern of the proposed 4×4 mmW array unit cell (a) with a 22.3 dBi gain at 28 GHz and (b) with a 24.1 dBi gain at 38 GHz.

FIGURE 14: Measured S-parameters and mutual coupling of the 4×4 mmW array unit cell.

FIGURE 15: Measured reflection coefficient S_{11} of the 4×4 mmW unit cell when connected to the modified WPD.

rate is achieved with BER of 2×10^{-3} at -50 dBm-received power. For further demonstration, Table 5 shows the received constellation diagrams for various modulation orders, at different transmitted power.

4. Conclusion

In this paper, a wide bandwidth and high-gain 4×4 antenna array unit cell is designed, fabricated, and tested for 5G wireless communication using an experimental testbed setup capable of generating standard digital modulation schemes over a carrier frequency of 28 GHz. The design of the proposed antenna array is based on a single SCVA, which has a wide impedance bandwidth from 25 to 40 GHz and high

gain with a value up to 13 dBi. The proposed 4×4 antenna array consists of four 1×4 SCVA linear arrays. Therefore, a M3WPD is designed, fabricated, and characterized for the purpose of operating as a corporate feed network for each 1×4 array. It has been demonstrated experimentally that the M3WPD provides wide bandwidth and good isolation among the input and output ports in the bands of interest. The 1×4 antenna array has an impedance bandwidth from 25 to 40 GHz and a gain of ~ 16 dBi in the end-fire direction. However, the proposed 4×4 antenna array unit cell works at the dual frequencies 28 GHz and 38 GHz providing wide bandwidths from 25 to 40 GHz and an average gain of ~ 23 dBi. The wireless transmission and reception of various digital modulation schemes, as

FIGURE 16: The proposed experimental setup. (a) Block diagram. (b) Measurements.

FIGURE 17: BER versus electrical received power for QPSK, 16QAM, 32QAM, and OFDM-16QAM at 1.5 m wireless distance.

presented in Section 3.2, have shown the promising evidence of the demonstrated unit cell as a candidate antenna array for next generation communication systems. A successful data transmission of 2.5 Gbps is achieved with a receiver sensitivity of -50 dBm and over 1.5 m wireless distance.

TABLE 5: Received constellations for various modulation schemes and transmitted power levels.

Transmitted power	-5 dBm	0 dBm	5 dBm	10 dBm
QPSK				
16 QAM				
32 QAM				
OFDM-16QAM				

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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