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A Novel Wideband Splitter for a Four-Element Antenna Array

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Abstract: In the paper, a novel design of a wideband power splitter for a four-element antenna array using two RF antiphase segments is proposed. Based on a detailed analysis of the power splitter circuit, an analytical model was set up in the MATLAB environment. The derived analytical model allows the development of a design of the described structure for any operating frequency and estimates the properties of the designed structure. In addition to the RF electrical part, the copper cover is also considered in this study. The copper cover serves as both a support and shielding part of the proposed structure. The electrical part consists of two sections of transmission lines. The first transmission line is symmetrical, while the second transmission line is asymmetrical. The given transmission lines can be realized using any technology (microstrip, coaxial, etc.). A prototype of the proposed wideband splitter operating at 650 MHz with a fractional bandwidth of 84.3% was designed and tested in real-world conditions to prove the concept. The board of the manufactured prototype has dimensions of 25 × 152 mm. A double-sided FR4 material with a substrate height of 1.48 mm, copper thickness of 50 µm, and $\epsilon_r \cong 4.3$, with a dielectric loss tangent of 0.021 was used to manufacture the prototype. The prototype was tested and its parameters were verified in practical conditions as a part of the current radio communication system for the 5G band. Under these conditions, verification measurements of the proposed splitter with a four-element antenna array were carried out.

Keywords: array antennas; bandpass filters; feeding networks; four-element antenna; power divider

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1. Introduction

Power splitters are important RF (radio frequency) devices, which have been used in modern communication systems and antenna arrays [1–5]. In the field of antenna arrays, the power splitters are crucial elements, which have a significant impact on the properties of a complete antenna array. For this reason, it is necessary to design an antenna array splitter with a low insertion loss, an optimal impedance matching, and a desired bandwidth. The essence of the presented article is the novel design as well as the implementation of the broadband antenna array splitter that enables a significant increase of the antenna gain, i.e., an increase of the antenna gain by at least 3 dB, and an optimization of the antenna radiation pattern in a large bandwidth.

The designed combiner is primarily intended for a broadband opposite-phase four-element antenna array. Such an antenna array consists of two pairs of elementary antennas. These two pairs are in anti-phase with each other. The first pair of antennas is connected to the first RF section, which is the RF transmission line for ports 1 and 2. The second pair of antennas is connected to the second RF section, which is the RF transmission line for ports 3 and 4. Ideally, the gain should increase fourfold. At the same time, the main lobe, defined as the half-power beam width (HPBW), should decrease fourfold.

However, the real improvements of both parameters are primarily limited by the splitter unit of the antenna array [3]. In the case of a splitter based on two anti-phase parts, the phase error factor is the most important parameter. In practice, a suitable value

of the phase error factor is usually around 1% or less. Other important parameters that quantify splitter properties are the transmission coefficient and the reflection coefficient of individual anti-phase segments of the splitter. In practice, the suitable value of the transmission coefficient for a four-element antenna array splitter is between −6.1 dB and −8.5 dB. Furthermore, the suitable value of reflection is less than −20 dB [1,4,6].

In this work, a novel concept of the broadband antenna array power splitter was applied. A power splitter that operates at a center frequency of 650 MHz with a fractional bandwidth of 84.3% was developed. Based on experiments performed with the manufactured prototype, a phase error factor of less than 0.65% in the working frequency range was achieved. The working frequency range is defined as a $S_{11} < -20$ dB bandwidth concurrently on both transmission lines.

Currently, the frequency band around 650 MHz is very attractive, since modern LTE and 5G communication technologies operate in this band. Moreover, the frequency band is also operated by DVB-T2 broadcasting systems. The described power splitter is therefore suitable for the abovementioned systems, where it could help cover more distant areas with better directional characteristics of a suitable antenna array. By using the proposed power splitter as a combiner, thanks to the principle of reciprocity, it is also possible to increase the power of the received signal in areas with limited coverage.

Furthermore, the transmission coefficient of the prototype ranges from −6.8 dB up to −8.4 dB, while the reflection coefficient of the prototype ranges between −20 dB and −26.5 dB. Thus, the theoretical and measurement results are in good agreement and show good performances in the working frequency band. The main contributions of the paper can be summarized as follows:

- The design of a broadband antenna array power splitter based on a novel concept of a combination of symmetrical and asymmetrical transmission lines;
- The experimental verification of the proposed power splitter in realistic conditions, on a 5G signal in the NR (new radio) band n14 with four identical log-periodic (LP) ultra-high frequency (UHF) FRACARRO LP45FMINI antennas;
- A proof of the design with excellent impedance characteristics, a large bandwidth, a low insertion loss and excellent phase accuracy for the sub-GHz band.

The rest of the paper is organized as follows. Related work is summarized in Section 2, the concept of the proposed antenna splitter is presented in Section 3, the results achieved from simulation and measurements are presented and discussed in Sections 4, and 5 concludes the paper.

2. Related Work

In this chapter, the state of the art and the results of the selected representative works in the field of RF splitters and dividers are presented and discussed. As mentioned above, the fundamental quantities that describe the properties of splitters and dividers are the transmission and reflection coefficients. From these fundamental characteristics, it is subsequently possible to derive additional quantities such as the flatness of the frequency response, insertion loss, and others.

One of the parameters used for the comparison with the related studies is the flatness of the frequency response of the reflection coefficient. This parameter specifies the range of variation in the reflection coefficient of a device over a given frequency range. The passband flatness of the reflection coefficient is specified in ±dB and is defined as the difference between the minimum and maximum values of the reflection coefficient in dB, measured over a given frequency range. The better the flatness of the reflection coefficient, i.e., the smaller positive number expressed in dB, the smaller the impedance changes over the considered frequency range. Smaller impedance changes in the passband result in a lower change of amplitude of the reflected power waves and standing waves.

Xu et al. [7] proposed a balanced-to-unbalanced micro-strip power divider that is based on branch lines with several stubs and a single resistor. The micro-strip power divider supports functions of power dividing, frequency selectivity, isolation between

output ports, and common-mode suppression. The authors claim that it is possible to control the bandwidth of the proposed power divider and the maximum bandwidth is achieved when the common-mode suppression and differential-mode response are the same. Tests were performed on two prototypes, and the first one achieved a 1 dB fractional bandwidth of 7.7% with a 0.6 dB insertion loss, while the second achieved a 1 dB fractional bandwidth of 5% with a 0.7 dB insertion loss, with the isolation and common-mode suppression better than 15 dB and 20 dB, respectively.

A compact wideband balanced-to-unbalanced out-of-phase power divider was proposed by Zhang et al. [8]. The proposed circuit consists of three pairs of cascaded coupled lined and a grounded resistor used for the isolation of the output, which resulted in good port matching, high output port isolation, and equal power division. The authors were able to achieve a fractional bandwidth of 37.2% and an insertion loss of 0.2 dB.

Feng et al. [9] proposed a four-port wideband power divider based on symmetrical transmission lines operating at 2.2 GHz with a fractional bandwidth of 89.1%. The minimum insertion loss of the proposed power divider was 3 dB and the reflection coefficient was less than −13 dB. The flatness of the frequency response of the reflection flatness was up to ±25 dB.

An ultra-wideband power divider based on a symmetrical three-port circuit, which operates at 6.85 GHz with a fractional bandwidth of 110%, was proposed by Wong and Zhu [10]. In the proposed design, the two output ports are properly linked with two identical step-impedance stubs and coupled lines. Based on the experimental measurements, the minimum insertion loss was 0.4 dB and the reflection coefficient was less than −12 dB. Moreover, the flatness of the frequency response was up to ±25 dB.

A tunable balanced to unbalanced power divider that divides the power from a balanced input port to unbalanced output ports was proposed by Yadav in [11]. The divider was proposed to divide the power in a specific radio by changing the biasing voltage. The power division ratio was changed by tuning of the capacitance, which was realized by the varactor diode.

Another three-port wideband power divider based on coupled lines operating at 2.3 GHz with a fractional bandwidth of 47% was proposed by Feng et al. in [12]. In this case, the minimum insertion loss was 1 dB and the reflection coefficient was less than −13 dB. The achieved flatness of the frequency response was up to ±12 dB.

Another three-port array-antenna feeding network operating at 2.5 GHz with a fractional bandwidth of 20% was proposed by Gomez-Garcia et al. [13]. The proposed design is based on a novel concept of a two-way signal-interference power divider configuration with added filtering functionality. Based on the presented experimental results, the minimum insertion loss was about 0.7 dB and the reflection coefficient was less than −3 dB. According to the provided results, the flatness of the frequency response was up to ±22 dB.

A high power-handling wideband power divider was proposed by Tadayon et al. in [14]. The power-handling capability was achieved by using grounded 50 Ω loads. In the experimental evaluation of the designed power divider, the reflection coefficient was less than −15 dB and insertion losses of about 0.5 dB were achieved over a 52% fractional bandwidth in the frequency range from 7 up to 12 GHz.

A fully self-packaged in-phase power divider with a wideband bandpass response was presented by Feng et al. in [15]. In this case, the three-port power divider was designed based on a four-port coupled-line common-mode network by keeping one of the ports shorted. The prototype was manufactured using multilayer liquid crystal polymer circuit technology. The operating frequency of the proposed power splitter was 2 GHz with a fractional bandwidth of 80%. Based on the experimental results, the achieved insertion loss was about 0.75 dB and the reflection loss was 15 dB.

A Gysel type unbalanced-to-balanced (UTB) power divider (PD) with arbitrary power division was proposed by Yadac et al. in [16]. The UTB PD was proposed as a five-port device with arbitrary power division. The developed UTB PD was designed for a 2 GHz frequency and a power division ratio of 1:2. Based on the experimental measurements

performed at the prototype of the proposed power divider, a fractional bandwidth of 21% and an insertion loss of about 0.56 dB were achieved.

A novel design of a ring-cavity multiple-way power divider with UWB performance was presented by Song and Xue in [17]. In the proposed design, a UWB coaxial taper feeding port was used to provide uniform excitation for the ring-cavity parallel power divider with large numbers of power-dividing ports. A prototype of a 32-way UWB ring-cavity power was manufactured. During experimental measurements, good amplitude and phase balance, very low loss, and very flat group delay were achieved.

A dual-band Wilkinson power divider with a high power split ratio was proposed by Nguyen et al. [18]. The authors replaced high transmission lines with dual-band T-shaped sections. A dual-band power divider with a power split ratio of 7:5:1 was fabricated and tested. The authors concluded that their design achieved a high split ratio, and good insertion loss, isolation, and return loss.

A planar 14-way radial power combiner with a two-octave bandwidth was proposed by Javid-Hosseini and Nayyeri in [19]. The authors claimed that the main advantage of the proposed solution is the ease and economy of manufacturing thanks to the use of standard PCB material. According to the presented results of experimental measurements, the output port was matched better than −10 dB and the amplitude balances were better than ±0.75 dB. The fabricated combiner had an average intersession loss of 2 dB; moreover, the authors claimed this could be further reduced with a low-loss dielectric substrate.

Song et al. proposed a four-way out-of-phase slotline power divider in [20]. Based on the achieved results, acceptable input impedance matching, low insertion loss, and good amplitude balance were achieved. On top of that, the proposed design of a power divider demonstrated reasonable isolation among the output ports. The authors concluded that the advantages of the proposed design are its compact size, wide operating bandwidth, good input–output impedance matching, low insertion loss, good amplitude balance at the output ports, and reasonable isolation among the output ports. Therefore, the solution should be very competitive in real-world applications in 5G networks.

Rahadi et al. proposed a meander line-based Wilkinson power divider for the 433 MHz frequency band in [21]. The application in mind was communication with UAV. The proposed design was based on the implementation of a meander line design on the quarter-wavelength transformer. Based on the presented results, the return loss was 19.05 dB, the insertion loss was 3.25 dB, and the port isolation was 26.53 dB. Moreover, the authors claimed that the proposed power divider has a linear phase, and that therefore there are no distortions to the phase nonlinearity.

An extension of the operation bandwidth of the Wilkinson power divider by the replacement of the quarter-wave transmission line with an impedance transformer was demonstrated by Yu in [22]. The author provided details on the design of the power divider with the structure of three segments. Based on the measurement results, a −20 dB fractional operation bandwidth of 101% was achieved, which is better than for traditional Wilkinson power dividers with a total length of $\lambda/4$.

Osman et al. described a single-stage two-way Wilkinson power divider for Internet of Things applications in [23]. The design was based on a single-section meandered line Wilkinson power divider with an open stub network and a defected ground structure. Based on the presented results, the proposed power divider achieved a fractional bandwidth of 107% with a central frequency of 600 MHz.

3. Proposed Antenna Array Splitter

The proposed splitter was designed for the frequency band of 650 MHz and is based on a pair of transmission lines. The first transmission line is asymmetrical and its length is a quarter wavelength of the medium operating frequency. Therefore, the electrical lengths of transmission lines should be 90°. The second line is symmetrical and has the same length as the asymmetrical transmission line. The characteristic impedance of the asymmetrical transmission line Z_{0a} is the same as the characteristic impedance of the used RF system

Z_0, which is normally 50 Ω or 75 Ω. The characteristic impedance of the symmetrical transmission line Z_{0s} is in the range between 1.6 × Z_0 and 3.2 × Z_0. The proposed circuit of the antenna array splitter is shown in Figure 1.

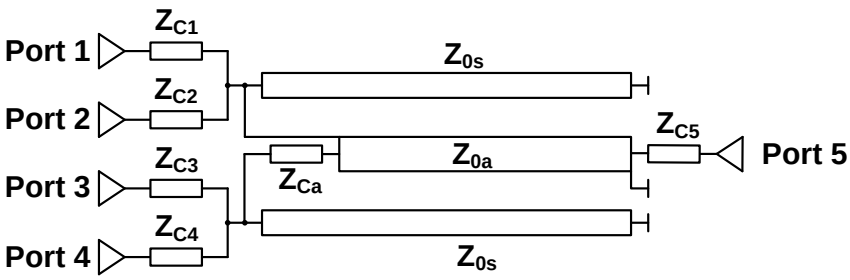

Figure 1. Proposed circuit of the wideband splitter for a four-element antenna array.

The first part of the proposed wideband splitter consists of a transmission line for input ports 1 and 2. These are connected to the first section of the symmetrical transmission line through coupling elements Z_{C1} and Z_{C2}. Similarly, the second part of the proposed wideband splitter consists of a transmission line for input ports 3 and 4. These are connected to the second section of the symmetrical transmission line through coupling elements Z_{C3} and Z_{C4}. The load of the symmetrical transmission line is a short circuit.

In practice, it is desirable to realize this load as a non-inductive element with a maximum impedance of 10 Ω in the whole working frequency range [1,3]. The coupling elements Z_{C1}, Z_{C2}, Z_{C3}, and Z_{C4} are considered to be identical RF components that realize the appropriate coupling of the antenna array to the proposed splitter structure. Subsequently, the symmetrical transmission line feeds the asymmetrical transmission line. The ground point of the asymmetrical transmission line is connected directly to the first part of the symmetrical transmission line. The trace point of the asymmetrical transmission line is connected via coupling element Z_{Ca} to the second part of the symmetrical transmission line. Finally, the output of the asymmetrical transmission line feeds through the coupling element Z_{C5} to the output connector of the splitter.

The central frequency of the proposed splitter depends primarily on the electrical length of the symmetrical transmission line, which should have exactly a quarter-wavelength at the central frequency. The bandwidth of the proposed splitter mainly depends on the characteristic impedance Z_{0s} of the symmetrical transmission line.

From the structure of the proposed power splitter, it is obvious that bandwidth is determined by the input impedance of the symmetric transmission line, which ends with a short circuit. In theory, the input impedance will be infinitely large and its influence will be negligible. For the other frequencies, within the bandwidth, the input impedance is given by the following relationship:

$$Z_{in} = j \times Z_{0s} \times \tan(\beta * l), \tag{1}$$

where Z_{in} is the input impedance, Z_{0s} is the characteristic impedance, and β is the phase constant of the transmission line with length l.

From the equation, it is obvious that the higher the characteristic impedance of the symmetrical transmission line Z_{0s}, the smaller the impact on the total impedance of the structure outside of the central frequency. Thus, the higher the value of the characteristic impedance of a symmetrical transmission line, the higher the bandwidth of the splitter and vice versa. However, the characteristic impedance is affected by the shielding cover [1–4].

When a shielding cover is used, the characteristic impedance of a symmetrical transmission line will decrease. The energy efficiency of the proposed splitter depends mainly on the quality of the used transmission lines. The energy efficiency of the transmission lines is defined as the ratio of the input power to the output power. Power losses in the

transmission lines can be caused by conductor heating, dielectric heating, and radiation losses. Thus, if low losses are required, it is necessary to use transmission lines with minimal power losses.

3.1. Synthesis Procedure of the Proposed Antenna Array Splitter

The characteristic impedance of the symmetrical transmission line Z_{0s} is significantly higher than the characteristic impedance Z_0 and has a significant effect on the electrical parameters of the proposed structure. The greater the value of the characteristic impedance Z_{0s}, the greater the bandwidth of the proposed splitter. On the other hand, the greater value of the characteristic impedance Z_{0s} can cause unwanted parasites that could disturb the phase symmetry of the proposed splitter. For a system with Z_0 = 50 Ω, the value of Z_{0s} ranges from 80 Ω to 160 Ω, and for a system with Z_0 = 75 Ω, the value of Z_{0s} ranges from 120 Ω to 240 Ω.

In addition, the value of the characteristic impedance of the symmetrical transmission line Z_{0s} is also influenced by the copper cover-supporting and shielding part of the proposed structure. The copper cover decreases the value of the characteristic impedance Z_{0s}. The consequence of this decrease in the impedance Z_{0s} is primarily a reduction in the bandwidth of the splitter. In the design of the combiner, it is necessary to respect the described effect of the shielding cover.

For this purpose, it is necessary to define an impedance decrease correction factor ξ. This correction factor can take values ranging approximately from 0.5 up to 0.95. Values closer to 0.5 represent a significant influence of the shielding cover, and on the other hand, values closer to 0.95 indicate a negligible influence of the shielding cover. These values depend on the mutual arrangement of the shielding cover with the proposed structure. The characteristic impedance of the symmetrical transmission line, taking into account the influence of the shielding cover, is subsequently calculated as a product of $\xi \times Z_{0s}$.

3.2. Prototype of the Proposed Antenna Array Splitter

Based on the above analysis, the prototype of the proposed antenna array splitter was designed and manufactured. The material used for the realisation of the prototype was double-sided FR4 with a substrate height of 1.48 mm, a copper thickness of 50 µm, and $\epsilon_r \cong 4.3$. The dielectric loss tangent of the material has a value of 0.021 and is assumed to be constant. The physical dimensions of the realized design are shown in Figure 2, where the black shape represents the copper structure of the proposed splitter. According to calculations performed using the online solver [24], for the given parameters of the structure, the electrical length is 91.02° at the center frequency of 650 MHz.

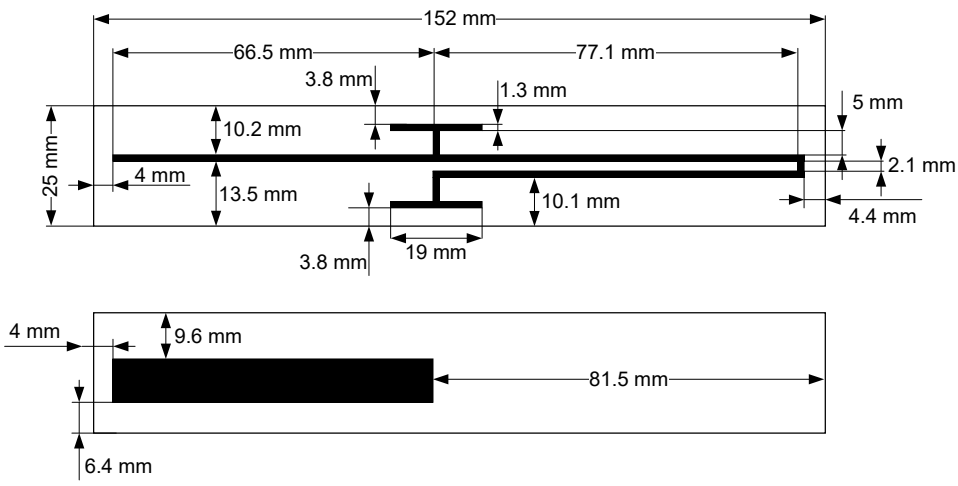

Figure 2. Schematic of the proposed antenna array splitter design with dimensions.

The characteristic impedance of the used RF system is 75 Ω and thus Z_{0a} = 75 Ω. To achieve the required bandwidth, the characteristic impedance of the symmetrical transmission line $\xi \times Z_{0s}$ should be equal to 185 Ω. To minimize the dimensions of the splitter, the distance between the shielding cover and the structure of the splitter was set to 10 mm.

This value of the correction factor ξ was estimated empirically based on the performed experiments. Since the distance of the shielding cover from the structure of the splitter is relatively low, the correction factor ξ reaches the value of 0.65. Therefore, it is necessary to design the characteristic impedance of the symmetrical transmission line to a value of 285 Ω. The manufactured prototype of the proposed splitter is shown in Figure 3a).

Figure 3. Manufactured prototype of the proposed antenna splitter: (**a**) manufactured board; (**b**) final splitter in the shielding case.

The proposed splitter structure was installed into the shielding cover, as can be seen from Figure 3b). The shielding cover is an important part of the proposed splitter and is uniquely designed and constructed according to the physical dimensions of the splitter structure. The fundamental part of the shielding cover is the carrying plate. On the carrying plate, there is a front plate, a rear plate, and right and left plates. Four input connectors are located in the front plate; one output connector is in the rear plate.

The cover also includes one support bar and one shorting bar, which are located inside the shielding cover. The splitter structure is covered by an appropriate lid. All parts of the shielding cover except for the support bar have a high specific conductivity. Connections of all parts of the shielding cover and connections of input and output connectors are precise without any electrical imperfections.

4. Achieved Results and Discussion

To estimate the parameters of the proposed power splitter, simulations were carried out in the MATLAB environment as well as using free-to-use software calculation tools for coplanar microstrip structures and their parameters [25,26]. Based on a detailed analysis of the power splitter circuit, an analytical model was programmed in the MATLAB environment. The programmed analytical model in MATLAB allows for the calculation and verification of all important characteristics of the proposed antenna splitter. The analytical model created in MATLAB will be made available on Matlab Central File Exchange (https://www.mathworks.com/matlabcentral/fileexchange/ (accessed on 1 January 2020)). The model mainly concerns the calculation of the frequency dependence of the following quantities:

- A transmission coefficient for segment A;
- A transmission coefficient for segment B;
- A phase error between segments A and B.

The calculation of these parameters was carried out based on input data. The essential input data for the correct calculation include:

- The physical length of the used transmission lines;
- The frequency dependence of the attenuation of the used transmission lines;
- The speed of propagation of the electromagnetic waves at the used transmission lines;
- The impedance of the coupling elements;
- The mutual arrangement of the splitter structure and shielding cover.

In the first step, the characteristic impedances Z_{0s}, Z_{0a} and propagation constants γ_s, γ_a of the used transmission lines were calculated. Since the proposed splitter is a passive reciprocal structure, the principle of reciprocity can be used for the required circuit analysis. The power source drives of the output port 5 and the response quantities on input ports 1 to 4 were analyzed. In accordance with the previous consideration, the parameters of the first fictive source, i.e., the internal voltage V_{f1} and internal impedance Z_{f1}, located at the output of the asymmetrical transmission line, were calculated. Subsequently, it is possible to estimate the parameters of two fictive sources that are located in the individual antiphase segments:

$$V_{f2A} = \frac{V_{f1} \times A}{2 \times (Z_{Ca} + 0.5 \times Z_{f1} + A)}, \tag{2}$$

$$V_{f2B} = \frac{V_{f1} \times A}{2 \times (0.5 \times Z_{f1} + A)}, \tag{3}$$

$$V_{f2A,B} = Z_C + \frac{1}{B}. \tag{4}$$

The quantities A and B in the equations above are artificial coefficients. These coefficients depend on the impedances Z_{f1}, Z_{0s}, Z_c, and Z_0, and are related to the division of voltage in the individual parts of the proposed structure. Subsequently, it is possible to calculate the voltages at the output load impedances. The voltage V_{12} for the first segment, i.e., the transmission line for port 1 and port 2, and voltage V_{34} for the second segment, i.e., the transmission line for port 3 and port 4, can be calculated as follows:

$$V_{12} = \frac{V_{f2A} \times Z_0}{Z_0 + Z_{f2A,B}}, \tag{5}$$

$$V_{34} = \frac{-V_{f2B} \times Z_0}{Z_0 + Z_{f2A,B}}. \tag{6}$$

Based on the equations above, it is subsequently possible to calculate the scattering parameters for individual antiphase elements of the proposed splitter.

In order to verify the design of the proposed splitter simulations, measurements were performed at the prototype of the proposed splitter. The results achieved in both the simulations and measurements of the proposed splitter are shown in the following figures.

The measurements were carried out on a calibrated measuring system using a vector network analyzer R&S ZVL6 (VNA) and a personal computer with a general purpose interface bus (GPIB) interface, and the measurement setup is shown in Figure 4. The plot in Figure 5 shows the frequency dependence of the transmission coefficient of segment A, i.e., the transmission line for port 1 and port 2. From this dependence, it can be concluded that the insertion loss within the working frequency band ranges from 0.97 dB to 2.37 dB, while the insertion loss at the center frequency reaches the value of 1.1 dB.

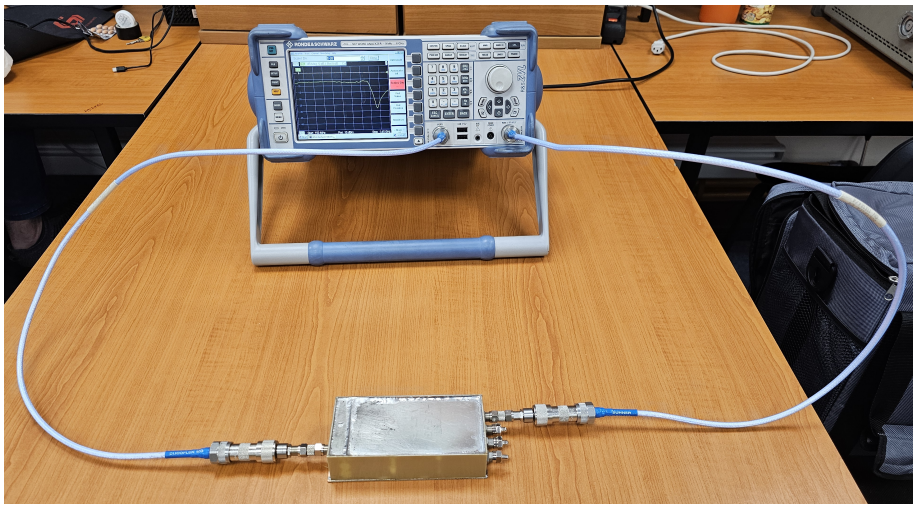

Figure 4. Measurement setup with power splitter connected to the vector network analyzer.

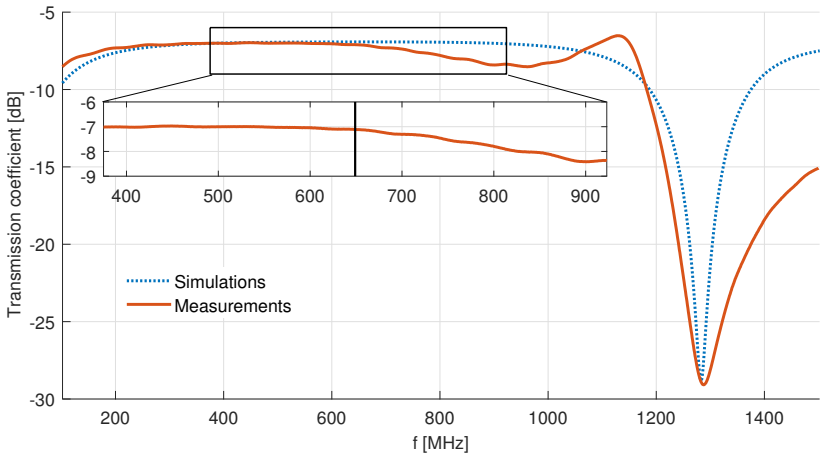

Figure 5. Impact of frequency on the transmission coefficient achieved from the simulation and measurements of the proposed antenna array splitter prototype on segment A (the transmission line for ports 1 and 2).

Figure 6 shows the frequency dependence of the transmission coefficient of segment B, i.e., the transmission line for port 3 and port 4. From this dependence, it is clear that the insertion loss within the working frequency band ranges from 0.57 dB to 1.47 dB. The insertion loss at the center frequency reaches the value of 0.6 dB. From the presented results it can be concluded that the proposed splitter has an extremely flat transmission response of ±0.8 dB within the working frequency band.

In Figure 7, the frequency dependence of the reflection coefficients of both segments is presented. Segment A represents the transmission line for port 1 and port 2, and segment B stands for the transmission line for port 3 and port 4. From this dependence, it can be concluded that the impedance difference of port 1 and port 2 from the reference value of Z_0 within the working frequency band is between 9% and 20%. The impedance difference at the center frequency for these ports reaches the value of 16%. Moreover, the impedance difference between port 3 and port 4 from the reference value of Z_0 within the working frequency band ranges between 14% and 20%. The impedance difference at the center frequency for these ports reaches a value of 17%. Therefore, it can be concluded that the proposed splitter has very good impedance properties within the working frequency band.

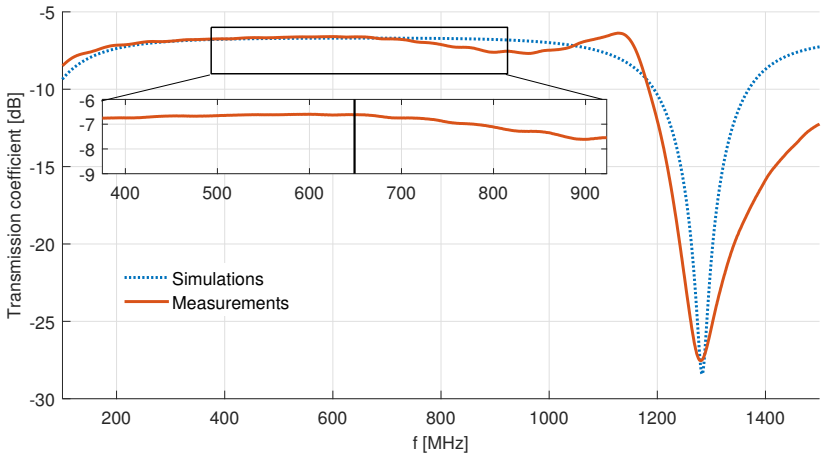

Figure 6. Impact of frequency on the transmission coefficient achieved from the simulation and measurements of the proposed antenna array splitter prototype on segment B (the transmission line for ports 3 and 4).

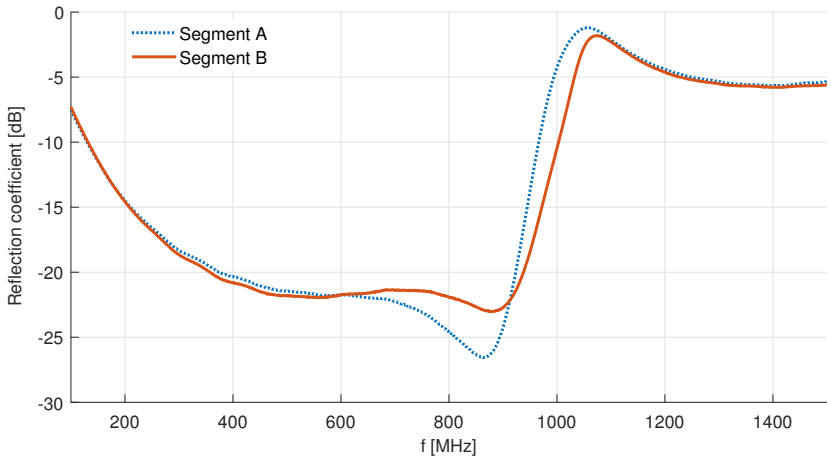

Figure 7. Impact of frequency on the reflection coefficients of both segments of the proposed antenna array splitter prototype based on experimental measurements.

The fractional bandwidth of the prototype can be calculated from the reflection coefficient, which has to be ≤ -20 dB for both segments of the transmission line. Based on the data presented in the figure, the cut-off frequencies are f_{min} = 375 MHz and f_{max} = 923 MHz. Thus, the fractional bandwidth for the center frequency f_c = 650 MHz can be calculated as follows:

$$B_{frac} = 100 \times \frac{f_{max} - f_{min}}{f_c} = 100 \times \frac{923 - 375}{650} = 84.3\%. \quad (7)$$

Figure 8 shows the frequency dependence of the phase error between the segments of the proposed antenna splitter from the simulation as well as the measurements. From this dependence, it follows that the phase error within the working frequency band ranges from 0.14% to 0.64%. The phase error at the center frequency reaches the value of 0.32%. Therefore, based on the achieved results, it can be concluded that the proposed splitter has excellent phase accuracy within the working frequency band.

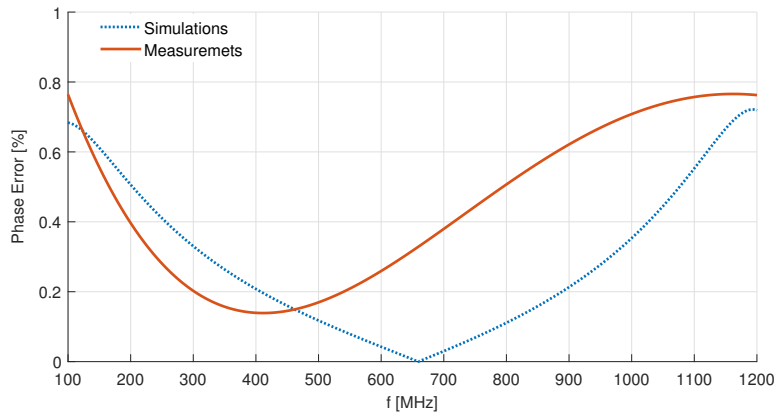

Figure 8. Impact of frequency on the phase error achieved during simulations and measurements of the proposed antenna array splitter prototype.

The properties of the proposed splitter were also verified in practical conditions for signals in the 5G NR band n14. Four identical LP UHF FRACARRO LP45FMINI antennas were connected to the prototype of the splitter to perform the measurements. The parameters of the antennas are summarized in Table 1. The measured results of the realized prototype of the proposed splitter under these conditions are shown in Figures 9 and 10. In this case, the measurements were carried out on a calibrated measuring system using a spectrum analyzer (SA) R&S ZVL6 and a personal computer with a GPIB interface. Since the beamwidth of a single antenna is ±25°, it could be assumed that the beamwidth of a four-antenna array is reduced to ±12.5° in both the E and H planes.

Table 1. Parameters of the FRACARRO LP45FMINI antennas.

Parameter	Value
Connector type	F connector, 75 Ω
Bandwidth	470–862 MHz
Gain	9 dBi
Front/back ratio	30 dB
Return Loss	−15 dB
Beamwidth (3 dB)	±25°

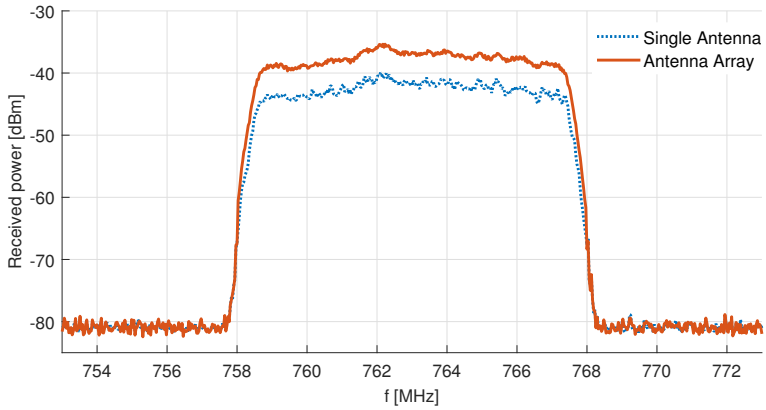

Figure 9. RF spectrum of the 5G NR band n14 measured by a single antenna and antenna array with a prototype of the proposed splitter.

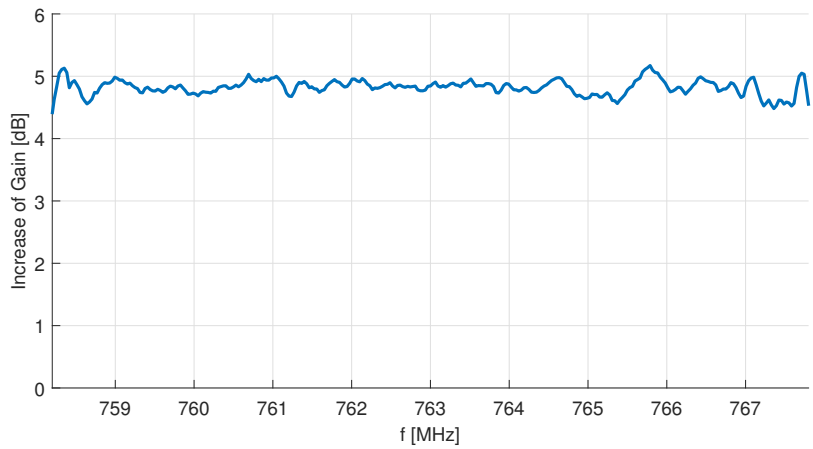

Figure 10. The increase of realized gain in the RF spectrum of the 5G NR band n14 using an antenna array with a prototype of the proposed splitter.

Figure 9 shows the 5G NR band n14 spectrum measured using a single antenna plotted using a dotted line. On the other hand, the solid line represents the received spectrum using a four-element antenna array with the proposed splitter. This plot shows that the realized gain of the antenna array with the proposed splitter has increased by approximately 5 dB compared to the realized gain of a single antenna.

The estimate of gain increase is shown in Figure 10. The increase in realized gain ranges from 4.5 dB to 5.1 dB, which is fully in accordance with the previous measurements in the laboratory conditions.

Table 2 shows the performance characteristics of the proposed solution with RF power dividers and splitters from the literature. Compared with current structures of RF splitters and dividers, the proposed antenna array splitter is characterized by excellent phase accuracy within a relatively high bandwidth, extremely flat transmission and reflection responses, low insertion loss, and excellent impedance matching. It is important to note here that the authors of the cited papers did not evaluate and present all the parameters compared in the table. Therefore, some of the values presented in the table are only estimates based on previously published results.

Table 2. Performance comparison of RF power dividers and splitters.

Reference	Number of Ports	Frequency Band (GHz)	Fractional Bandwidth	Insertion Loss (dB)	Reflection Coefficient (dB)	Reflection Flatness (dB)
[9]	4	2.2	89.1%	≥3	≤−13	±25
[10]	3	6.85	110%	≥0.4	≤−12	±25
[12]	3	2.3	47%	≥1	≤−13	±12
[13]	3	2.5	20%	≥0.7	≤−3	±22
[14]	5	7–12	52%	≥ 0.5	≤−14	±15
[15]	3	2	80%	≥3.75	≤−10	±14
[16]	5	2	21%	≥0.56	≤−10	±10
[17]	32	3.1–10.6	109%	≥0.7	≤−10	±29
[19]	15	3.75	120%	≥2	≤−10	±25
[20]	4	7	60.6%	≥0.4	≤−15	±9
[22]	3	0.5	101%	≥0.47	≤−20	±16
[21]	3	0.433	69%	≥3.37	≤−19.05	±5
[23]	3	0.6	107.7%	≥0.9	≤−10	±24
Proposed	5	0.65	84.3%	≥0.8	≤−26.5	±6.5

5. Conclusions

A novel wideband power splitter for a four-element antenna array using two RF antiphase segments is proposed. The proposed antenna array power splitter achieved an extremely flat transmission response, an excellent phase accuracy, a relatively high bandwidth, and low insertion loss. The parameters of the proposed power splitter were evaluated through both simulations and measurements. It is important to note that there was a good agreement between the simulated and measured results.

The properties and simulation results of the proposed splitter were verified with measured under practical conditions in the current 5G system. Measurements of the proposed antenna array splitter confirmed the parameters achieved from the simulations performed in a Matlab simulation model. The proposed splitter achieved an insertion loss of less than 0.8 dB, a reflection coefficient of less than −26.5 dB, and a reflection flatness of ±6.5 dB, which makes it superior to other state-of-the-art solutions.

Future work will be focused on the modification of the antenna splitter structure for other frequency bands. Moreover, further optimization of the proposed antenna splitter will be performed to improve the design and achieve better characteristics in terms of reduced power loss, improved impedance matching, and improved symmetry of individual segments. Moreover, the minimization of the physical dimensions while maintaining the presented parameters and minimization of the parasitic elements in the structure can represent further areas of future work.

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