Wideband Planar Four-Element Linear Antenna Array

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***Abstract*—This letter presents a planar wideband linear antenna array to cover multiple wireless standards. The array consists of four microstripline-fed open-ended quarter-wavelength slot antenna elements. By feeding the antenna properly, a fundamental radiating antenna mode can be excited over a wide frequency range. The antenna array is simulated in terms of surface current distributions and S-parameters. Simulated results are compared to the manufactured prototype antenna array. Measured results show the -10-dB impedance bandwidth is from 2.55 to 6.1 GHz, corresponding to 83% relative impedance bandwidth, while mutual coupling is less than -16.6 dB within the aforementioned impedance bandwidth. The simulated -10-dB bandwidth is from 2.0 to 6.0 GHz. Measured radiation patterns are presented at 2.4, 3.5, and 5.2 GHz with 4.6, 7.0, and 7.9 dBi maximum gain in boresight direction, respectively. The measured radiation patterns and grating lobe levels correlate well with the theory and are 10–15 dB below the main lobe depending on the studied frequency.**

***Index Terms*—Array factor, cognitive radio, fundamental antenna mode, multiple-input–multiple-output (MIMO) antenna, slot antenna, smart antenna, software defined radio.**

I. Introduction

REMARKABLE progress in mobile communications systems has occurred in the last decade. Nowadays, fourth-generation (4G) systems (LTE Advanced) are already widely used, and research is now focusing on future wireless systems (5G). As mobile phone and wireless systems get more advanced, more radio interfaces are needed at both ends of the wireless link.

Multiple antennas improve the signal-to-noise ratio (SNR) at the receiver and suppress co-channel interference in a multiuser scenario, thus improving the signal-to-interference-plus-noise ratio (SINR) at the receiver(s). Both goals can be achieved by means of beam-steering techniques. Another technique that requires multiple antennas at both ends of the wireless link is called multiple-input–multiple-output (MIMO).

Software defined radio (SDR) and cognitive radio (CR) are two concepts in wireless communications that have changed the way that radio systems are designed and operated. These changes have significant effects on antenna requirements in a host of applications from mobile phones to satellite communications. Both concepts imply capabilities for operation over very wide bandwidths. For handheld radio antennas, bandwidth and efficiency at low frequencies is the main problem. When considering base-station antennas, the difficulty of designing very wideband antenna arrays lies in the pattern control [1].

There are several types of antennas to cover wide frequency range: frequency-tunable [2], [3]; reconfigurable [4], [5]; and wideband antennas [6], [7]. When it comes to wideband antenna arrays, Vivaldi or tapered slot antenna arrays are quite generally used [8], [9]. Also patch antennas [10], loop antennas [11], and bow-tie antennas [12] are studied in the literature.

This letter proposes a wideband four-element linear antenna array. A planar microstripline-fed open-ended quarter-wavelength slot antenna element is used in an array, based on the structure presented in [13]. The differences between structures are different feedlines and the increased thickness of the metal conductor of the antenna element. By increasing the antenna thickness, the impedance matching can be improved. It is shown that by placing antenna elements at 0.36–0.8λ (2.4–5.2 GHz) distance, the measured radiation patterns keep the form of a linear array over the aforementioned bandwidth. Additionally, the operating principle of an individual antenna element is presented. The idea is to excite the fundamental antenna radiating mode over a wide frequency range as shown in terms of surface current distributions.

The antenna array covers the UMTS (2.1 GHz), Bluetooth (2.4 GHz), WLAN (2.45 and 5.1–5.8 GHz), DVB-SH (S-band), LTE (2.0–3.8 GHz), and WiMAX (2.3–5.7 GHz) standards with 83% measured relative impedance bandwidth (-10 dB). For comparison, slot antennas presented in [13]–[15] provide 100%, 85%, and 95% (relative impedance bandwidths -6 dB), respectively. As the antenna array operates over wide frequency range, one practical solution can be found in wireless LAN access point systems [16], [17].

The letter is organized as follows. Section II presents an individual antenna element, operating principle, and prototype antenna. Simulations and measurement results are presented and compared in Section III. Finally, Section IV contains conclusions and a discussion of the proposed planar wideband linear antenna array.

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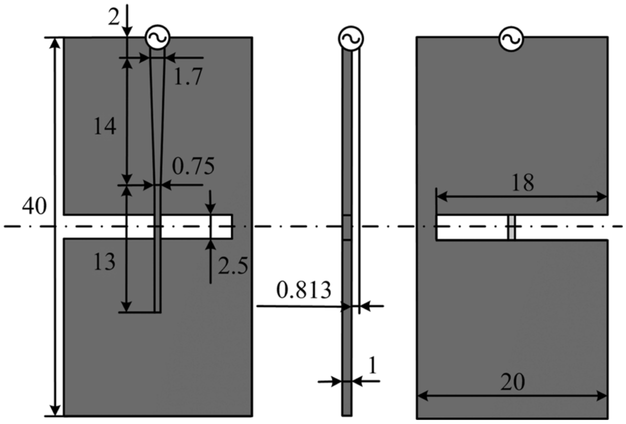

Fig. 1. Individual antenna element in an array with dimensions (in millimeters).

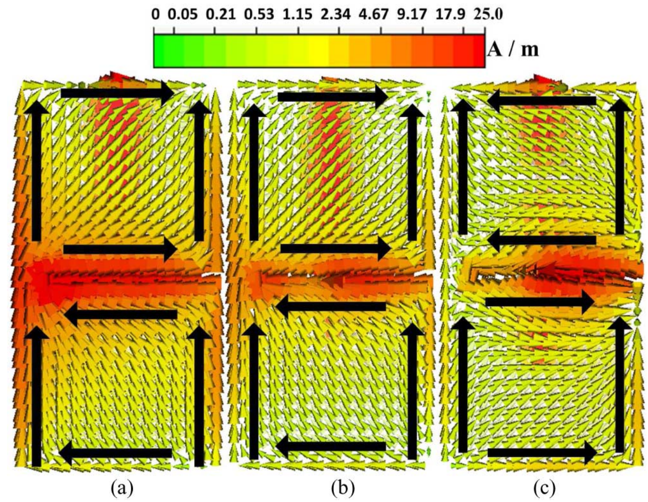

Fig. 2. Surface current distributions of the antenna element at (a) 2.4, (b) 3.5, and (c) 5.2 GHz.

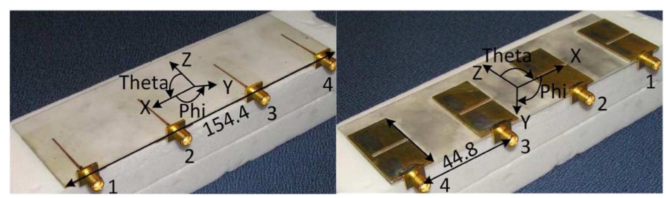

Fig. 3. Prototype antenna with dimensions (in millimeters) and coordinate system.

II. Antenna Structure

This section describes the proposed antenna array structure in terms of array elements spacing, individual antenna element in an array with dimensions and its surface current distributions at 2.4, 3.5, and 5.2 GHz. In addition, a four-element prototype antenna with dimensions and coordinate system is presented.

A. Element Spacing

In this section, we discuss a compromise for antenna element spacing in a linear antenna array while keeping grating lobe level of a radiation pattern as low as possible. It is essential because when the physical spacing of antenna elements is fixed, the electrical spacing in terms of wavelength (λ) increases at higher frequencies, and the radiation pattern of an array is modified.

The formula to calculate the normalized array factor for an N-element linear array can be found in [9] and [19]. As theory shows [9], the grating lobe level significantly increases with element spacing bigger than 0.8λ. At 0.8λ antenna spacing, the main beam of an array factor can be found in direction $\phi = \pm 90^\circ$. Additionally, the grating lobe level for the four-element linear arrays remains less than -12 dB and resides in $\phi = 0^\circ$ and $\pm 180^\circ$ [9].

B. Individual Antenna Element and Its Current Distributions

The antenna element used in a linear array is presented here, whereas the antenna array itself is described in Section II-C. The antenna element is based on an idea presented in [13] where a planar quarter-wave open-ended slot antenna is fed with microstripline.

Fig. 1 presents the dimensions of an individual antenna element in millimeters. Rogers4003 RF-laminate with 0.813 mm thickness is used. The antenna conductor thickness is 1 mm and is made by soldering a plate of brass to the other side of the substrate. On the other side of the substrate is the conventional microstripline to feed the antenna.

The operating principle of the antenna structure presented in Fig. 1 is the same as in [14]; the fundamental mode is excited over a wide frequency range, when, at the same time, the imaginary part of the input impedance remains around zero. This is achieved with a complementary behavior of a magnetic slot (capacitive) and an electric conductor (inductive). More information about the input impedance can be found in [14].

Fig. 2 presents the current distributions of the antenna element at 2.4, 3.5, and 5.2 GHz. When comparing the results to [14], it can be observed how the fundamental mode is excited at every studied frequency with vertically polarized current distributions. Notice that horizontal currents propagate in opposite directions in the lower and upper parts of the antenna element. Thus, the horizontally polarized current components are canceled.

C. Wideband Linear Antenna Array Prototype

Fig. 3 presents the proposed linear antenna array prototype. In the array, four elements described in Section II-B are equally spaced with 0.8λ distance at 5.2 GHz. Thus, the physical spacing at 5.2 GHz is 44.8 mm, which equals 0.36λ at 2.4 GHz.

The array is fabricated on Rogers4003 RF-laminate. The white foam below the array is a supporting material made of Rohacell ($\varepsilon_r \approx 1$). For comparison, the size of the proposed antenna array is the same as the reconfigurable antenna in [5].

III. Results

This section presents simulated and measured antenna element and array performance. The commercial 3-D electromagnetic simulator CST Microwave Studio with time domain solver is used in all the simulations.

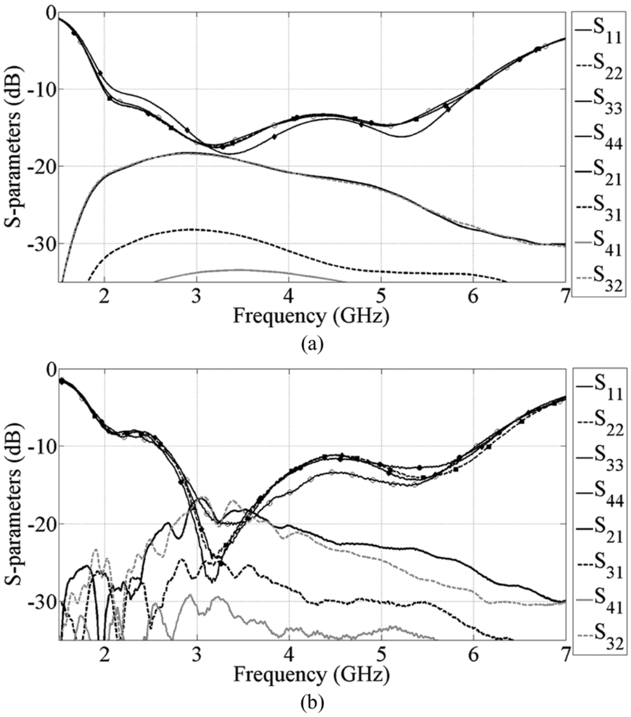

Fig. 4. (a) Simulated and (b) measured S-parameters of the antenna array.

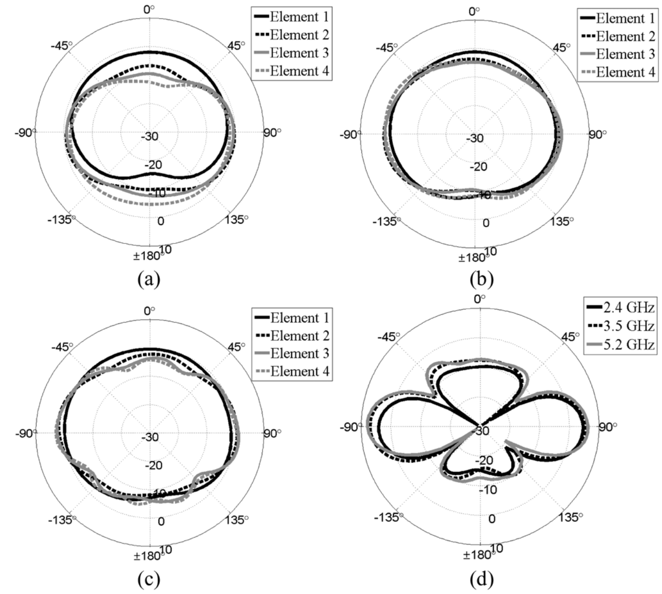

Fig. 5. Radiation patterns of individual elements in the linear array in xy-cut at (a) 2.4, (b) 3.5, and (c) 5.2 GHz. In (d), radiation pattern of the linear wideband antenna array is presented at previously mentioned center frequencies. Radiation patterns are presented in terms of total gain (dBi).

First, S-parameters are presented, and simulations are compared to the measured ones. Second, the measured radiation properties of individual antenna elements are presented. Then, the antenna array radiation properties are presented without beam steering at 2.4-, 3.5-, and 5.2-GHz center frequencies.

A. S-Parameters

Fig. 4 presents the simulated and the measured S-parameters of the prototype antenna. It can be observed in Fig. 4(a) that the simulated relative -6-dB bandwidth of the array is slightly increased compared to the structure in [13]: 100% against 113% presented in this letter. This indicates that the mutual coupling between antenna elements does not disturb the impedance bandwidth of the array. A typical reference value in mobile applications [18] for input impedance is -6 dB. For comparison, the simulated relative -10-dB impedance bandwidth of the proposed antenna array is 100% (2–6 GHz), which is typically used with antenna arrays [8].

In Fig. 4(b), the measured S-parameters are presented. One can observe the -10-dB impedance bandwidth does not fully correlate with the simulations in the lower end of the spectrum, from 2 to 2.55 GHz. The measured relative -10-dB impedance bandwidth is 83% (2.55–6.1 GHz). The reason for difference between simulations and measurements was found to be in manufacturing tolerances; the soldering of the 1-mm-thick brass plate to the RF-laminate is very sensitive to heat differences.

However, results correlate well with the theoretical maximum relative impedance bandwidth of a square-shaped planar conducting plate studied in [18], where the simulations predicted 95% relative bandwidth. For comparison, in [20], the relative -10-dB impedance bandwidth achieved with four-element linear array is 64%, and in [10] 44.5%, respectively. Additionally, the presented results are very similar to [12], where achieved relative -10-dB impedance bandwidth is 91%.

When it comes to the simulated isolation between antenna elements, there is good correlation with the measurements. The maximum measured isolation between elements is 16.6 dB, when the simulations are predicting 17.4 dB. The measured average isolation over -10-dB impedance bandwidth is 21 dB. This well correlates with the average isolation between two bow-tie antenna elements in [12], which is 18 dB.

B. Radiation Patterns

This section presents the measured radiation patterns of an individual antenna element and the method of how the results are combined to linear antenna array radiation patterns.

The measured radiation patterns of an individual antenna element are presented in Fig. 5(a)–(c) at 2.4, 3.5, and 5.2 GHz, respectively. The radiation pattern of the array is calculated by summing the complex far field of individual antenna elements at the studied center frequency. The following formula is used to move the reference point of the measured antenna elements to the middle of the linear array [21] (see the coordinate system in Fig. 3):

$$\mathbf{G}_A(\theta,\phi) = \mathbf{G}(\theta,\phi)e^{jk\mathbf{r}_A\cdot\hat{\mathbf{r}}} \quad (1)$$

where $\mathbf{G}_A(\theta,\phi)$ represents an antenna array gain in far field as a function of θ and ϕ, $\mathbf{G}(\theta,\phi)$ is a gain in far field of individual antenna elements in an array, $k = 2\pi/\lambda$, $\mathbf{r}_A$ is displacement of antenna element from the origin, and $\hat{\mathbf{r}}$ is a unit vector.

By following (1), the radiation patterns of the proposed linear antenna array are presented in Fig. 5(d) without beam steering. This means that the amplitudes of all antenna elements are equal, and the phase differences are zero. To measure antenna radiation patterns, the embedded element pattern method is used, as presented in [20]. The method allows measuring an antenna array without feed network.

The maximum gain of the antenna array is 4.6, 7.0, and 7.9 dBi at 2.4, 3.5, and 5.2 GHz, respectively. The maximum gain is found on the direction of boresight ($\text{theta} = 90°$, $\text{phi} = \pm 90°$), and the measured radiation pattern well correlates with the measured results of the four-element linear array presented in [20].

When studying the grating lobes, it can be observed they well correlate with the theory, as discussed in Section II-A. The grating lobe levels are, depending on studied frequency, from -10 to -15 dB below the main lobe and can be found in direction $\text{theta} = 90°$ and $\text{phi} = 0°/180°$. These results also well correlate with the ones presented in [20].

The measured grating lobes and main lobes are not symmetrically drawn into the polar plot as shown in Fig. 5(d). This is due to asymmetrical radiation properties of an individual antenna element. On the other hand, the radiation of the active element is directive to the direction of a parallel passive element. Thus, other elements for Element 1 are acting as a directive element. The effects of this directivity can be easily seen, especially at 2.4 GHz [Fig. 5(a)], where antenna elements are electrically closer to each other than other studied frequencies.

IV. Conclusion and Discussion

The letter proposed a wideband linear antenna array. The antenna consists of four planar microstripline-fed open-ended quarter-wavelength slot antenna elements to excite the fundamental radiating antenna mode over a wide frequency range. The antenna presented a good impedance matching and isolation properties between the antenna elements over -10-dB operating bandwidth. Also, correlation between theoretical, numerical, and measured results was observed to be good.

Wideband antenna arrays for multiple radio interfaces increase the demands for filtering compared to reconfigurable or narrowband antennas. Whereas an antenna with narrow bandwidth is automatically filtering the signal, wideband antennas need adjustable filtering that adapts quickly to the operating frequency in question. On the other hand, wideband antennas can be considered simpler than reconfigurable antennas as there are no additional components (e.g., for frequency or radiation pattern tuning).

As the antenna element spacing gets wider in terms of wavelength when operating frequency increases, the array can be considered to be utilized in MIMO systems. The antenna element spacing can be increased from 0.38λ to be greater than 0.8λ at 2.4 GHz to support MIMO up to 6 GHz. This also decreases mutual coupling and spatial correlation between the antenna elements.

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