Int. J. Electron. Commun. (AEÜ) 70 (2016) 1172–1178

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

A side-fed spiral antenna for near-field coupler applications

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ARTICLE INFO

Article history:
Received 18 October 2015
Accepted 30 May 2016

Keywords:
Spiral-antenna
Near field
Coupler antenna

ABSTRACT

Wireless devices with no direct access to ports are tested by antenna couplers, which are designed to have wideband performance and an omni-directional radiation field profile for uniform near-field coupling with positional variation. The spiral antenna coupler presented here is designed to be used in a RF-shielded enclosure, requiring a metal backing ($\lambda/83$ away at 0.4 GHz in this study) to preserve consistent performance, but can also be used separately. The design is a stripline fed spiral antenna with mixed Archimedean and Equiangular antenna equations describing the spiral expansion of the arms. Absorbing material placed around the antenna removes resonances/reflections on the metal backing and reflections from the antenna's open end. The infinite balun stripline feed is shown to provide high return loss over the required frequency range of 0.4–6 GHz. The antenna near- and far-field performance, as well as coupling between identical antennas are measured with and without metal backing to demonstrate the performance as an antenna coupler.

1. Introduction

Spiral antennas are valued for their wideband matching and radiation efficiency. Additionally, their radiation patterns are naturally circularly polarized and omnidirectional [1]. The two most common spiral antenna design types are Equiangular [2] and Archimedean [1], which differ in the equations used to describe the geometry of the spiral arms. Spiral antennas are typically fed at the center of the spiral arms [3–5], but many designs feed the antenna from the side [6–11]. In both cases, impedance matching is required to efficiently feed the spiral antenna design since the ideal impedance of a self-complementary spiral antenna is 188Ω [12]. An infinite balun involves the use of an integrated transmission line reference conductor feeding the antenna. It prevents common-mode currents from propagating to the antenna, which helps maintain a consistent radiation pattern [13]. The tapered transmission line provides ultra-wideband impedance matching by allowing the signal line's impedance to match that of the antenna's input impedance at the spiral's center, while simultaneously matching the source impedance at the side feeding point [6–8,11,14]. Other impedance matching techniques can be used [5], but they have the downside of greatly increasing the thickness profile of the antenna and providing poorer wideband performance.

The applications of such antennas can vary from the detection of partial discharge from gas insulation substations [15] to specialized radar applications [16]. The antennas of mobile and other wireless devices are not externally accessible, so performance testing must therefore be made over the air (OTA). The link between the device under test (DUT) and an antenna coupler must be reliable and well-characterized, such that testing over a range of operating frequencies can be easily accomplished. Additionally, the near-fields of the coupler should be uniform, so that coupling is reliable and consistent with varying DUT placement. These factors make spiral antennas the most desirable choice of antenna coupler design.

To be used in a radio-frequency (RF) shielded enclosure (ex. Testforce Systems Inc. [17]), the designed antenna must have a low physical profile consistent near-field patterns across the frequency range of operation (400 MHz to 6 GHz in order to cover all relevant bands of most common wireless DUTs), as well as high coupling with closely placed antennas. Many of the spiral antennas previously reported in the literature are designed for higher frequencies [4–11,13,16,18–20], and those designed for lower frequencies are much larger, do not include workable impedance matching, and/or do not reach the upper frequency range required in this design [9,15,21,22].

For many applications, including near-field coupling in a shielded enclosure, the use of a metallic backing on one side of the spiral antenna for unidirectional radiation is desired [15,18]. This metallic backing has a strong influence on the wideband characteristics of the antenna and efficiency of radiation [3,4]. There-

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http://dx.doi.org/10.1016/j.aeue.2016.05.015
1434-8411/

fore, the use of microwave absorbing materials to eliminate surface waves and reflections from the metallic backing is common [3].

The antenna coupler designed in this study is described as follows: a micro-miniature coaxial (MMCX) connector connects a coaxial feedline to a short coplanar waveguide transmission line at the side of the antenna, which transitions to an infinite tapered stripline balun. The signal line of the stripline connects to the radiating arms of the antenna at the antenna's center. The simulation and measurement of the radiation and near-field characteristics are detailed. The coupling performance with closely placed devices is demonstrated and characterized by examining the coupling to an identical antenna. Tests with and without a metallic backing are completed. The near-field and far-field performance is measured, and the variation of coupling with antenna height (distance from the metallic backing to the spiral antenna) is investigated. The antenna is found to have consistent return loss, independent of the presence of the metallic backing.

Key findings/results in the development of the antenna coupler are:

(1) The design of a minimally sized spiral antenna with wideband (0.4–6 GHz) performance;
(2) Impedance matching through the use of an infinite stripline balun feeding with signal and ground plane design using mixed Archimedean and Equiangular spiral equations;
(3) The characterization of the spiral antenna with and without a metallic backing in terms of near-fields and coupling.

2. Geometry and patterns

The final geometry of the antenna, designed to work from 0.4 GHz to 6 GHz, is shown in Fig. 1(a). The manufactured antenna is shown in Fig. 1(b). The approximation used for the minimum operating frequency is [1,18]

$$\frac{c}{2\pi r_{max}} = f_{min}, \tag{1}$$

where the radius r_{max} is measured with respect to the side of the antenna, as shown in Fig. 1(a). With a f_{min} of 400 MHz r_{max} would be required to be 119 mm, but the r_{max} of the coupler is limited to 84 mm (570 MHz) by design constraints. It will be shown that high radiation efficiency, gain and return loss is still obtained at the lower operating frequency without the metallic backing, although maintaining circular polarization is not feasible with this constrained antenna size.

The operational bandwidth can be determined based on a number of different criteria: return loss, efficiency, gain and axial ratio are common examples. The determination of the lowest operating frequency of the proposed antenna can be compared to the literature based on the stated frequency range, or (when available) the minimum frequency for which a gain of 0 dB is obtained. This point will be shown to be approximately 400 MHz for the non-metal backed antenna in this study. In the literature, the ratios of wavelength to antenna diameter – for which a larger value indicates a greater degree of miniaturization – following the criteria stated are: 1.9 [3], 2.5 [4], 2.5 [5], 3.1 [6], 3.0 [7], 3.0 [8], 2.2 [10], 3.5 [11], 1.7 [13], 1.7 [14], 1.9 [15], 1.7 [16], 1.8 [18], 2.4 [19], 1.7 [21] and 3.1 [22]. In this study the ratio is 4.4, which is larger than the values found in the cited literature.

The antenna is manufactured with Rogers RT/duroid 5880 ($\varepsilon_r/tan\delta$ of 2.2/0.0009). The layers of the transmission line portion of the antenna are arranged vertically in the following order: ground, substrate, signal line, substrate, ground. In Fig. 1(c), the vias that connect the two grounds at the corner connection are visible. The grounds of a MMCX connector (modeled according to specifications of TE Connectivity AMP connectors MMCX connector, part number 1-1634010-0) are connected to the antenna, while the center pin is connected to the signal line of a short length of coplanar waveguide. The corner connection is designed so that the MMCX connector can be connected on either the top or bottom side of the antenna.

The coplanar waveguide signal line is 1 mm wide with 0.25 mm side gaps to provide a characteristic impedance of 50 Ω. The coplanar waveguide leads to a via that is connected to the signal line of a stripline transmission line section as shown in Fig. 1(c). The width of the stripline signal line is 1.2 mm, while the widths of the ground lines are 21 mm. The stripline transmission line ground and signal lines begin to transition into a spiral after a length of half the antenna diameter.

The curves traced by the inner and outer copper edges for both the signal line and top and bottom ground lines can be described using the relation

$$r = s\phi + r_0 e^{\alpha_1 \phi} + w_0 e^{\alpha_2 \phi}, \tag{2}$$

where r is the distance from the center, r_0 is the initial radius, α_i is the growth rate, ϕ is the polar angle and s is the linear expansion rate. The combination of the Equiangular [2] and Archimedean [1] spiral equations provides greater design flexibility, and allows the benefits and tradeoffs of both spiral types to be considered. Broader arms, as with an equiangular spiral, can reduce loss. With the Archimedean spiral, more turns improves impedance matching and bandwidth. A demonstration of the spiral expansion and its relation is shown in Fig. 2.

The spiral arms have 4.5 turns; the number is kept low to reduce transmission line losses. The values of s, w_0 and r_0 are $1/\pi$, 0.595 mm and 1.275 mm. The expansion coefficients α_1 and α_2 are 1/7.29 and 1/37 for the signal lines and 1/7.6 and 1/8 for the ground lines, respectively. Widths approximately equal to those of the stripline transmission section are achieved where the spiral and stripline transmission sections meet. At the antenna's center, the transmission structure cannot be described simply as a stripline transmission line, since the ground and signal lines have the same width and the spirals of the antenna are in close proximity to each other.

The center connection in Fig. 1(d) is accomplished by use of a via, and an additional unconnected embedded line is included as labeled in Fig. 1(d) to preserve symmetry [8]. The infinite balun involves the use of a long transmission line which tapers to a structure with the desired input impedance at the center, and the use of the transmission ground for one end of the antenna provides a balanced feed. Finding the width at the center that provides the best impedance match was accomplished by iteratively varying w_0 between 0.2 mm and 2 mm.

At the center of the antenna, the ground lines of the transmission line are unconnected and act as one of the spiral arms of the radiating antenna coupler. The signal line is connected with small triangular-shaped connections to the other spiral arms of the antenna, which have the same geometry as the ground lines but possess the opposite rotational sense. At the other end of the antenna spiral arm, it was tested whether a short, open, or 50 Ω termination with the unconnected embedded line would provide better performance. It was found in simulation that the open termination provided the best return loss and radiation performance by a small amount, and is therefore used in the manufactured antenna.

The performance of the antenna when backed with a metallic plate is investigated with an optimized separation of 9 mm. For comparison, the cavity height is $\lambda/83$ at the lowest frequency of 0.4 GHz, as opposed to the cavity height of $\lambda/14$ at the lowest operating frequency of 3 GHz in reference [18]. Absorbing material is placed between antenna and metallic backing. ECCOSORB LS-24