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Using Near-Field Coupled Circularly Polarized Antennas as Frequency Independent Variable Phase-Shifters

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This paper introduces a novel concept of frequency-independent variable phase-shifters. It is based on the use of circularly polarized (CP) antennas coupled in the near-field. For transmission between two CP antennas in the far-field, a rotation around the boresight axis produces a phase change in the transfer function. This concept is exploited and validated also for near-field coupling between two CP antennas. Therefore, two close-coupled CP antennas can act as a adjustable phase-shifter with the phase-shift controlled by the angle between the structures. The bandwidth depends on the CP bandwidth of the antenna. This concept is valuable for future phase-shifters in mm-wave applications where rotation can be facilitated by MEMS elements.

Introduction: Phase-shifters have a wide range of applications in wireless communications, specifically in multiple antenna system beam forming networks. There are two types of phase-shifters – true delay line phase shifters, which introduce a phase-shift increasing linearly with frequency, and frequency-independent phase shifters. The latter have been investigated for more than 50 years [1].

All designs known in the open literature rely on coupled-line structures which are reported to provide stable wideband phase-shifts, e.g. [1] reports phase error <3° for frequencies 3.1-10.6 GHz. The advantage of this structure is its compact size and low insertion loss, but the structure offers only a constant phase-shift. Attempts to control the phase-shift were made by using a multilayer structure where the distance between the coupling elements is varied by activation of switches between coupling apertures at different layer levels [2]. The issue of this approach is that for each step in phase-shift, an additional layer is required. Thus the complexity of the structure does not allow for fine phase steps.

In this paper, we therefore propose the novel concept of a frequency independent phase-shifter which inherently offers variable phase-shift without compromising the bandwidth. First, the transfer function between two CP antennas in far-field is discussed and it is shown that the transfer function phase depends on the relative antenna rotation. This concept is then shown to also hold for near-field coupling of two prototype antennas thereby representing a low-complexity variable phase-shifter. Limitations of the method as well as future applications are then discussed.

Transmission between two CP antennas: Inspired by [3], the transfer function $H(f) = S_{out}(f)/S_{in}(f)$ for signal transmission between two, for now unspecified, antennas in far-field as shown in Fig. 1 can be written as:

$$H(f) = \frac{c_0 \exp\left(-j2\pi \frac{f}{c_0} r\right)}{j4\pi f r} \begin{pmatrix} H_{2X}(f) \\ H_{2Y}(f) \end{pmatrix}^T \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} H_{1X}(f) \\ H_{1Y}(f) \end{pmatrix} \qquad (1)$$

where f is the frequency, c_0 is the speed of light, r is the distance between antennas, and H_{iX} is the transfer function between the input voltage wave at the port of antenna i and the electric field E_{iX} in direction x (in antenna's respective coordinates) caused by the input voltage wave [3]. H_{iY} is then the equivalent quantity for the second polarization direction [3]. The middle diagonal matrix accounts for the mutual position of the coordinates of the antennas (see Fig. 1).

A rotation of antenna 1 with respect antenna 2 by angle φ (axis z_1 and z_2), i.e. creating an angle φ between the axis x_1 and x_2 in Fig. 1, translates (1) into:

$$H(f) = \frac{c_0 \exp\left(-j2\pi \frac{f}{c_0} r\right)}{j4\pi f r} \begin{pmatrix} H_{2X}(f) \\ H_{2Y}(f) \end{pmatrix}^T \begin{pmatrix} \cos\varphi & \sin\varphi \\ \sin\varphi & -\cos\varphi \end{pmatrix} \begin{pmatrix} H_{1X}(f) \\ H_{1Y}(f) \end{pmatrix} \qquad (2)$$

For CP antennas, the relationship between $H_{iX}(f)$ and $H_{iY}(f)$ is known to be [4]:

$$H_{iX}(f) = \pm j \operatorname{sgn}(f) H_{iY}(f) \qquad (3)$$

where $\pm$ describes the direction of the polarization (right- or left-handed) and sgn() represents the sign function.

Substituting (3) into (2) yields:

$$H(f) = \frac{c \exp\left(-j2\pi \frac{f}{c} z\right)}{j2\pi f r} H_{2X}(f) H_{1X}(f) \operatorname{sgn}(f) \exp(j\varphi) \qquad (4)$$

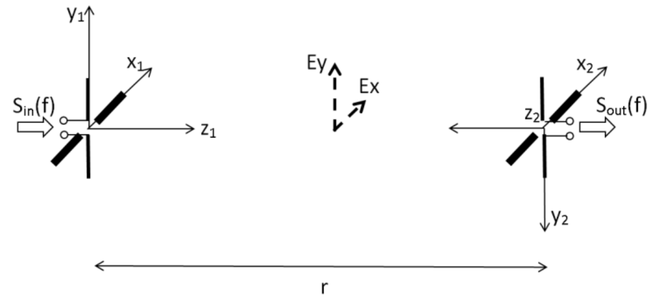

Fig. 1 *Transmission between two antennas described by Eqn (1) with definition of their respective coordinates*

Eqn (4) has the following meaning. A rotation displacement by angle φ results in a phase shift of φ. This effect is known and described as an adverse effect [4, 5]. Reference [4] shows that this effect means that a wideband signal transmitted by CP antennas changes its waveform with rotation. Reference [5] then discusses the adverse effect of Eqn (4) on vertical precision in GPS where the rotation of the receiver causes an integrated phase error.

The novelty of this paper is in the attempt to use Eqn (4) as a benefit. It can be seen that in the far-field link described above, a rotation of one antenna causes a phase-shift which is frequency-independent, limited only by the CP antenna bandwidth. With antennas such as dual-arm spirals which have a theoretically infinite impedance and CP bandwidth, Eqn (4) offers a blueprint for frequency-independent variable phase-shifters. The issue is the far-field requirement resulting not only in very large structures, but also in unacceptably high insertion loss.

Application to near-field coupling: In the near field, the concept of circular-polarization is not defined because radial fields components are also present. However, even the near-field exhibits a field rotation. Thus the hypothesis is that the concept described for far-field using Eqn (4) is also applicable to CP antennas coupled in the near-field.

To confirm this hypothesis two structures from Figs. 2 and 3 are investigated. Fig. 2 introduces a wideband dual-arm logarithmic spiral antenna fed by a balun. This structure has optimized CP performance for the band 3.5 to 6 GHz. Fig. 3 then introduces a narrowband patch antenna which produces CP in the band 3.58-3.62 GHz.

For the experiment, two antennas of each type were placed face-to-face, separated by a distance of 15 mm (<0.3 λ_0 for all operating frequencies). One antenna was rotated whilst the transfer function between the ports was recorded using the Rohde & Schwarz ZVA 40 Network Analyzer.

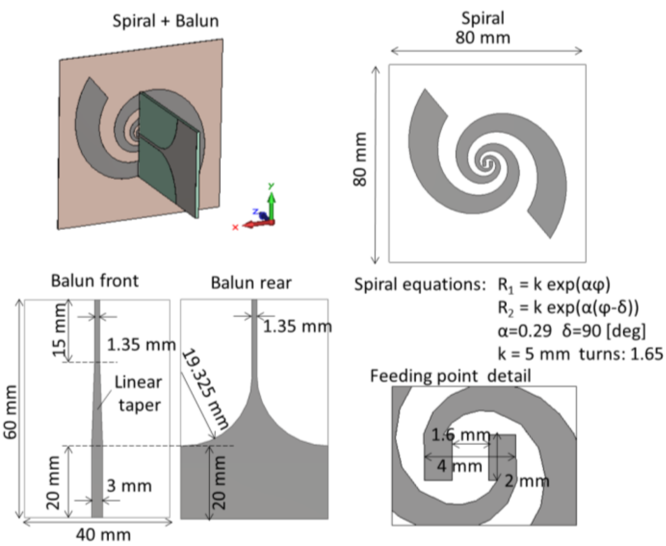

Fig. 2 *Wideband dual-arm logarithmic spiral antenna. The spiral is printed on FR-4 substrate of thickness 0.25 mm, the balun is on FR-4 substrate of thickness 1.6 mm.*

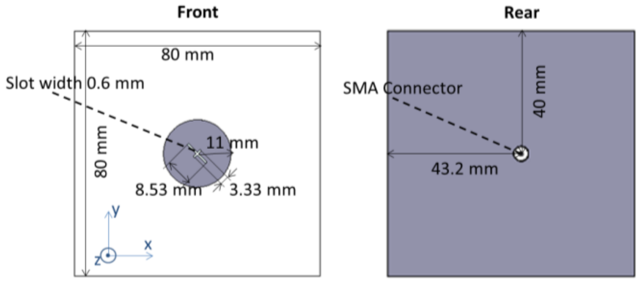

Fig. 3 *Circular patch antenna producing CP at 3.58-3.62 GHz. The substrate used is FR-4 of 1.6 mm thickness*

The measured phase-shifts (compared to perfect antenna alignment) are shown in Figs. 4 and 5 for the wideband dual-arm spiral and the narrowband microstrip patch antennas, respectively. Both figures show the phase-shift for antenna rotation from 10° to 90°, in 10° steps.

Fig. 4 confirms the hypothesis that a very wideband phase-shift can be achieved by rotation of one antenna. The phase-shift increases with rotation angle. The error in the phase-shift increases with rotation angle, but despite this, the results clearly demonstrate the possibility to provide wideband frequency-independent phase-shifts over relative bandwidth greater than 50%.

Fig. 5 shows that even for the circular patch the rotation can be used to control the phase shift; for the CP band 3.58-3.62 GHz highlighted in Fig. 5, the phase error is less than 2° for all the reported rotations 10° to 90°. Even though a wideband phase-shift is not exhibited here, it demonstrates that the concept depends on the nature of the field excited by the antenna (CP in far-field) rather than on a specific architecture.

Conclusion and Future Work: The results show that a new class of variable ultrawideband/frequency-independent phase-shifter can be designed. The phase shifter consists of two elements that can be independently rotated on a common axis. The rotation of the elements by angle φ introduces a frequency-independent phase shift φ, if the elements excite a rotating field (which in the cases presented here results in CP in the far-field).

Even though the designs presented here do not yet have the properties required by industrial applications, because in terms of size, phase-shift stability and insertion loss, they are outperformed by conventional couplers such as [1], it is believed that the value of the contribution is in the novelty and previously unreported approach towards frequency-independent phase-shifters. The main advantage of the concept is that unlike conventional phase shifters, this approach offers an inherently variable phase-shift over a wide range of frequencies with limitations imposed only by the bandwidth in which the required near-field properties can be excited (in the examples here it is the CP bandwidth).

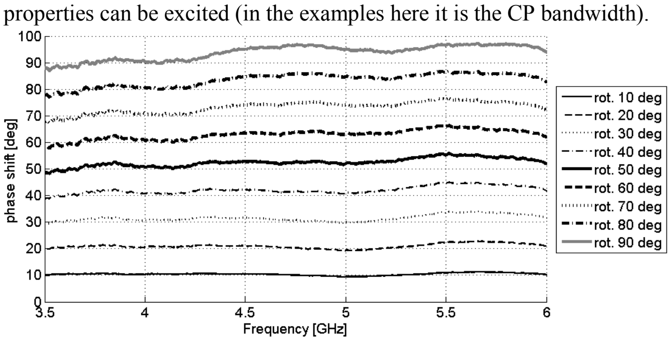

Fig. 4 *Phase shift due to rotation of one antenna for the coupling between two wideband spiral antennas from Fig. 2*

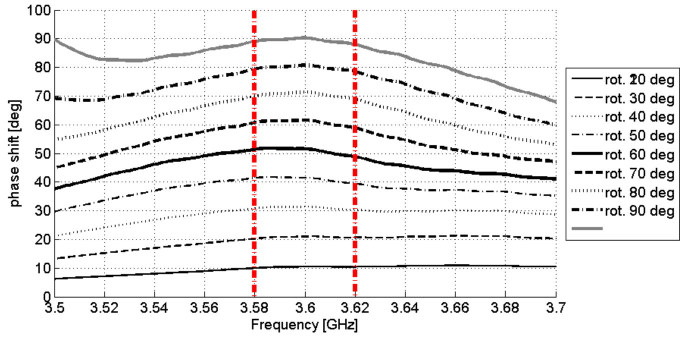

Fig. 5 *Phase shift due to rotation of one antenna for the coupling between two circular microstrip patch antennas from Fig. 3*

Future work will focus on the miniaturisation and improvement of the insertion loss. Currently for antenna spacing of 15 mm, the insertion loss is 9 dB for the dual arm spiral and 5.6 dB for the circular patch.

These drawbacks can be addressed when near-field coupling techniques known from RFID and wireless power transfer systems are used. This concept can alongside with MEMS devices represent an interesting new avenue for the development of variable frequency-independent phase-shifters for mm-wave applications.

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References

1. Abbosh, A.M.: "Ultra-Wideband Phase Shifters," *Microwave Theory and Techniques, IEEE Transactions on* , vol.55, no.9, pp.1935-1941, Sept. 2007

2 Shamsinejad, S., Mousavi, P.: "Novel 4 states variable UWB phase shifter," *Antennas and Propagation Society International Symposium (APSURSI), 2013 IEEE* , vol., no., pp.784-785, 7-13 July 2013

3 Duroc, Y., Tan-Phu Vuong; Tedjini, S.: "A Time/Frequency Model of Ultrawideband Antennas," *Antennas and Propagation, IEEE Transactions on* , vol.55, no.8, pp.2342-2350, Aug. 2007

4. Foltz, H.D., McLean, J.S.; Medina, A., Alvarez Jerkov, J.H.: "Lack of Rotation Invariance in Short-Pulse Communication Between Broadband Circular-Polarization Antennas," *Antennas and Propagation, IEEE Transactions on* , vol.58, no.11, pp.3747-3751, Nov. 2010

5. Kline, P.A.: "Atomic Clock Augmentation For Receivers Using the Global Positioning System," *PhD. Thesis*, Virginia Tech, 1997