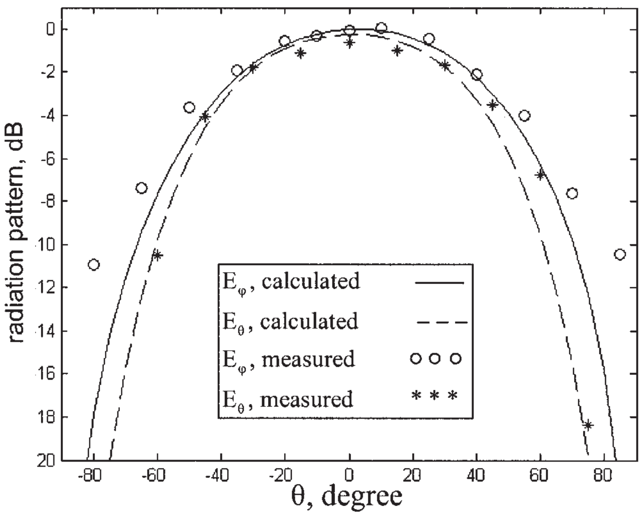

Figure 4 Two sets of predicted and measured radiation patterns on the *y–z* plane

actual circumference of the proposed spiral-loop antenna is significantly reduced by ~33%. This CPS-fed CP antenna will be very useful for exploring a new class of printed CP array using the CPS feeding technique, as in [3, 5].

REFERENCES

1. H. Morishita and K. Hirasawa, Wideband circularly polarized loop antenna, Proc IEEE AP-S Int Antennas Propagat Symp Dig 2 (1994), 1286–1289.
2. H. Morishita, K. Hirasawa, and T. Nagao, Circularly polarised wire antenna with a dual rhombic loop, IEE Proc Microwave Antennas Propagat 145 (1998), 219–224.
3. B. Strassner and K. Chang, 5.8-GHz circularly polarized dual-rhombic-loop travelling-wave rectifying antenna for low power-density wireless power transmission applications, IEEE Trans Microwave Theory Tech 51 (2003), 1548–1553.
4. S. Makoto, H. Kazuhiro, and S. Shi, Two rectangular loops fed in series for broadband circular polarization and impedance matching, IEEE Trans Antennas Propagat 52 (2004), 551–554.
5. L. Zhu and K. Wu, Model-based characterization of CPS-fed printed dipole for innovative design of uniplanar integrated antenna, IEEE Microwave Guided Wave Lett 9 (1999), 342–344.

APPLICATION OF COMPLEMENTARY SPLIT-RING RESONATORS TO THE DESIGN OF COMPACT NARROW BAND-PASS STRUCTURES IN MICROSTRIP TECHNOLOGY

Jordi Bonache,[1] Ferran Martín,[1] Francisco Falcone,[2] Juan D. Baena,[3] Txema Lopetegi,[2] Joan García-García,[1] Miguel A.G. Laso,[2] Ignacio Gil,[1] Antonio Marcotegui,[4] Ricardo Marqués,[3] and Mario Sorolla[2]
[1] Department d'Enginyeria Electrònica
Universitat Autònoma de Barcelona
08193 Bellaterra (Barcelona), Spain
[2] Departamento de Ingeniería Eléctrica y Electrónica
Universidad Pública de Navarra
Campus Arrosadía
E-31006 Pamplona, Spain
[3] Departamento de Electrónica y Electromagnetismo
Universidad de Sevilla
41012 Sevilla, Spain
[4] CONATEL s.l.
Sancho Ramírez, 1-3
31008 Pamplona (Navarra), Spain

Received 28 February 2005

ABSTRACT: *In this paper, a compact and narrowband microstrip band-pass structure based on complementary split-ring resonators (CSRRs) etched in the back metal level (ground plane) is presented. Specifically, the structure is a two-stage CSRR-based device, where a series gap is etched in the output CSRR stage and two shunt stubs are added in the input cell. By these means we obtain a narrow and quite symmetric band-pass structure. A prototype device with 2% fractional bandwidth has been designed and fabricated for operation at the S-band. The dimensions of the device are as small as 14.6 × 11 mm, while high-frequency selectivity is achieved at both band edges due to the presence of two transmission zeros. To demonstrate the possibility to control the bandwidth over a narrow band, a wider (10% bandwidth) filter has been also designed and fabricated. These structures can be of interest for application in narrow band-pass filters where miniaturization and compatibility with planar technologies are key issues.* © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 46: 508–512, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21031

Key words: *complementary SRRs; duality; microstrip technology; microwave filters*

1. INTRODUCTION

Ever since the first experimental verification of left-handedness [1], the number of works devoted to artificially fabricating materials (metamaterials) able to exhibit the unique electromagnetic properties predicted by Veselago [2] in the late 1960s has dramatically increased. These properties (namely, the reversal of Snell's law, the Doppler effect, and Cherenkov radiation) are closely related to backward-wave propagation, which is in turn due to the simultaneous negative values of dielectric permittivity ε and magnetic permeability μ in the medium [2]. Among these left-handed materials (LHMs), also called double-negative (DNG) media, those based on split-ring resonators (SRRs) have attracted great interest. Proposed by Pendry [3], SRRs are subwavelength resonators that consist of a pair of concentric metal rings on top of a dielectric slab with splits etched in opposite sides (see Fig. 1). Arranged periodically, these constituent particles cause the structure to behave as an anisotropic effective medium with negative permeability in the vicinity of resonance [1]. Anisotropy comes from the fact that the magnetic field vector of incident radiation

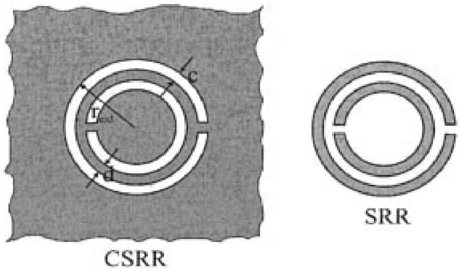

Figure 1 CSRR and SRR topologies and relevant dimensions

should have a nonnegligible component parallel to the rings axis. If this condition is satisfied, signal propagation is inhibited in that narrow band where μ is negative, since the propagation vector is purely imaginary, and only evanescent modes are supported by the structure. This behavior has been also interpreted as being due to the induced currents at resonance, which are closed through the distributed capacitance between concentric rings [4]. This means that SRRs can be modeled as a parallel LC resonant tank externally driven by a magnetic field.

The first planar negative-μ and LHM structures based on SRRs have been recently reported by the authors [5–7]. The proposed devices are coplanar waveguides (CPWs) with SRRs etched in the back substrate side, underneath the slots. With this topology, high inductive coupling between the line and the rings arises, and the structure exhibits stop-band behavior in the vicinity of resonance. By simply adding shunt-connected metal wires between the central strip and the ground planes etched at periodic positions, a plasmalike behavior is introduced to the structure, and the effective permittivity becomes negative up to a frequency that can be controlled by wire separation and width. If this frequency is set above the resonant frequency of the SRRs, an LHM band-pass filter with backward-wave propagation in the allowed band results.

Recently, a new constituent particle for metamaterial design has been proposed by some of the authors: the complementary split-ring resonator (CSRR) [8]. These particles (see Fig. 1) are the negative image of SRRs and hence are their dual counterparts. By virtue of Babinet's principle and complementarity, an axial time-varying electric field, rather than a magnetic field, is necessary to excite the rings. In microstrip technology, by etching an array of CSRRs in the ground plane, below the conductor strip, it has been found that signal propagation will be inhibited in the vicinity of their resonant frequency [8] (which should roughly coincide with that of SRRs with identical dimensions). However, from the point of view of an effective medium, this forbidden band has been interpreted as due to a negative value of permittivity. To obtain an LHM microstrip line, additional elements, able to provide the required negative permeability, have been introduced. These are series capacitive gaps, periodically etched in the conductor strip, above the positions of CSRRs (Fig. 2) [9]. From the equivalence between plane-wave propagation in an homogeneous isotropic medium and transverse *em* propagation in transmission lines, it follows that series gaps provide the negative effective permeability from dc up to a frequency where the series impedance of the line is no longer capacitive [10]. The resulting structure behaves as a narrow band-pass structure that supports backward-wave propagation in the allowed band. The measured frequency response of this structure, previously published [9] but also reproduced in Figure 2, shows a very sharp transition in the lower-band edge, but poor frequency selectivity in the upper transition band. In this paper, a new strategy to simultaneously achieve high-frequency selectivity at both band edges and compact device dimensions, is presented. This strategy consists of a combination of CSRRs with series gaps and shunt stubs. Whereas the CSRR/gap combination provides a sharp transition at the lower-band edge, shunt stubs combined with CSRRs provide also a sharp transition, but in the upper edge of the band. Two designed and fabricated prototype devices exhibit quite symmetric and highly selective frequency responses with only two CSRR stages, and thus indicate the possibility of controlling the device bandwidth within a narrow frequency interval. The strategy presented in this work allows for significant reduction in the device dimensions and hence this approach can be of interest for the design of narrow band-pass filters in planar technology.

2. DESIGN OF CSRR BAND-PASS FILTERS

The layout of the narrower fabricated filter is depicted in Figure 3. As can be seen, two CSRRs are etched in the ground plane, underneath the conductor strip. In the input CSRR stage, two grounded stubs are added to the upper metal level, whereas the CSRR/gap combination prevails for the second stage. The lumped-element equivalent-circuit models for the output and input stages are depicted in Figures 4(a) and 4(b), respectively. L and C are the inductance and capacitance of the line respectively, whereas C_g and L_p model the capacitance of the series gaps and the inductance of the shunt stubs, respectively. The CSRRs are modeled as resonant circuits electrically coupled to the line through the line capacitance C. These circuit models are valid, since the electrical length of the CSRR-based cells is small and the CSRRs are very close. These are necessary conditions in order to neglect the transmission-line effects between the input and output CSRR stages, although interaction (coupling) between adjacent CSRRs has not been taken into account.

The dispersion relation corresponding to infinitely long structures composed of the unit cells depicted in Figures 4(a) and 4(b) are given by

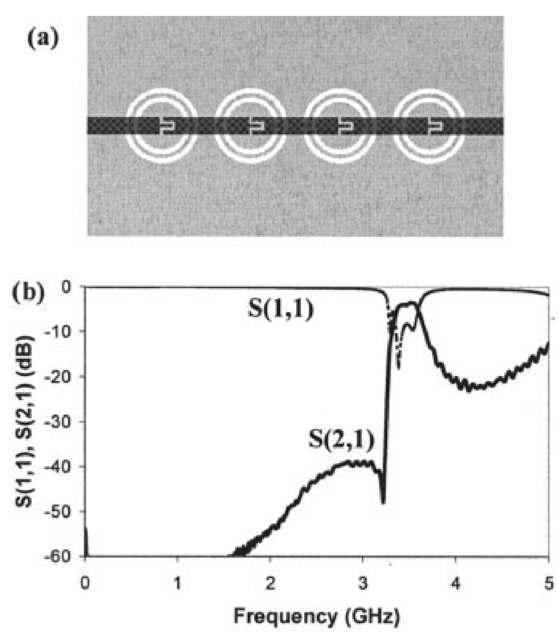

Figure 2 (a) Layout corresponding to a CSRR LHM microstrip band-pass structure and (b) measured frequency response. The period of the device, strip width, and gap spacing are $l = 6$ mm, $W = 1.2$ mm and $l_g = 0.2$ mm, respectively. CSRR dimensions have been determined to obtain a resonant frequency of $f_o = 3.5$ GHz [10], that is, $c = d = 0.3$ mm and $r_{ext} = 2.5$ mm (the parameters of the Rogers RO3010 substrate have been considered, namely, dielectric constant $\varepsilon_r = 10.2$ and thickness $h = 1.27$ mm)

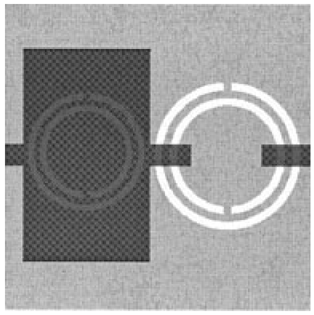

Figure 3 Layout corresponding to the designed CSRRs' microstrip band-pass structure combining shunt wires and series gaps. CSRR dimensions are $r_{ext} = 3.1$ mm, $c = 0.32$ mm, $d = 0.32$ mm and $r_{ext} = 3.9$ mm, $c = 0.4$ mm, $d = 0.4$ mm for the wire and gap rings, respectively. Gap spacing is $l_g = 3.7$ mm and wire dimensions (length and width) are $l_w = 11.2$ mm and $w_w = 6.7$ mm, respectively

$$\cos(\beta l) = 1 + \frac{L\omega - \dfrac{1}{C_g\omega}}{2\left(\dfrac{L_s\omega}{1 - L_sC_s\omega^2} - \dfrac{1}{C\omega}\right)} \tag{1}$$

and

$$\cos(\beta l) = 1 + \frac{L\omega^2\left[L_p + \dfrac{L_s}{1 - L_sC_s\omega^2}\right] - \dfrac{L}{C}}{2\left(\dfrac{L_sL_p\omega^2}{1 - L_sC_s\omega^2} - \dfrac{L_p}{C}\right)}, \tag{2}$$

respectively. According to Eq. (1), a periodic array of CSRR/gap unit cells allows backward-wave propagation in a narrow band between the frequency that nulls the shunt impedance (transmission zero frequency, $f_s = [L_s(C_s + C]^{-1/2}/2\pi)$ and the intrinsic resonant frequency of the CSRRs ($f_o = [L_s(C_s)]^{-1/2}/2\pi$). Between these two frequencies, the shunt admittance is inductive. Therefore, as long as the series impedance is dominated by C_g (in this frequency range), a periodic structure composed by these unit cells can be considered as a left-handed transmission line. For the structure depicted in Figure 4(b), due to the absence of C_g, signal propagation is only allowed in that region where the shunt admittance is capacitive. This occurs to the left of f_s, but to achieve a narrow band, the presence of the shunt inductor L_p is required. From these arguments, it follows that by cascading a single CSRR/gap stage with a CSRR/shunt unit cell, it is possible to synthesize a narrow pass band with transmission zeros at both edges. To this end, it is necessary to design the CSRR of either stage such that it exhibits the transmission zeros at different frequencies and to design both filter stages with an identical central frequency. This explains the different dimensions of the CSRRs for the input and output stages, as indicated in Figure 3. These dimensions have been inferred from the models given in [11, 12]. However, in practice, the size of CSRR as well as the dimensions of the gap and shunt inductors have been optimized in order to achieve a narrow band with the lowest level of in-band losses possible. This has been done by means of the commercial software Agilent Momentum, where the parameters of the Rogers RO3010 substrate have been considered, namely, dielectric constant $\varepsilon_r = 10.2$ and thickness $h = 1.27$ mm.

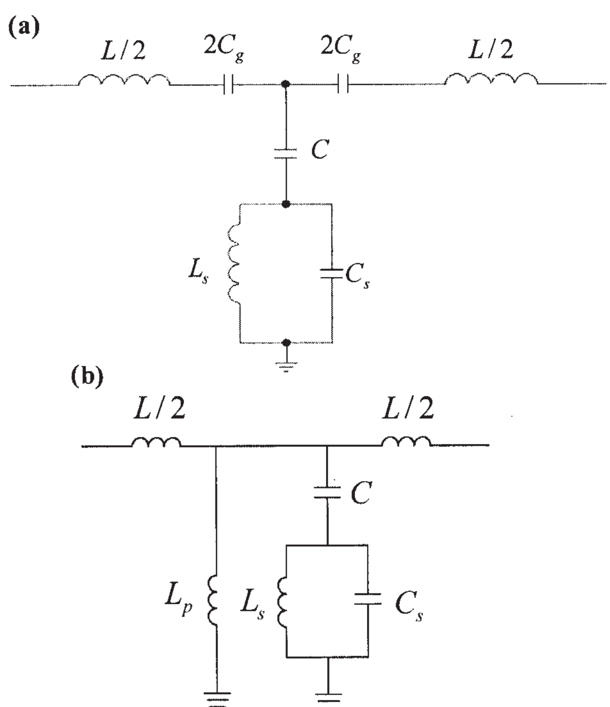

Figure 4 Equivalent T-circuit model for the (a) CSRR/gap and (b) CSRR/stub cells

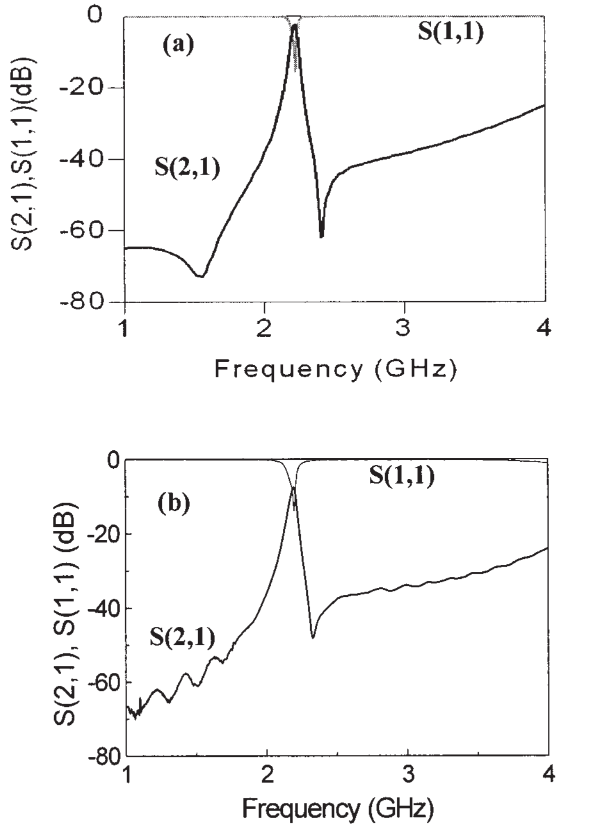

Figure 5 (a) Simulated and (b) measured frequency responses for the device in Fig. 3

3. RESULTS

The simulated frequency response corresponding to the final device topology is depicted in Figure 5. The device has been fabricated by means of a standard photo/mask etching technique, whereas a metallization process was previously practiced in order to ground the shunt stubs through metallic vias. After soldering the connectors to the ports, the frequency response of the device has been measured by means of the Agilent 8720ET vector network analyzer. The results are also depicted in Figure 5. These results show good agreement with those of the simulations. A narrow pass band centered at 2.2 GHz has been obtained with sharp transition bands at both band edges. The out-of-band performance is good, with rejection levels larger than 30 dB up to 4 GHz. The slight discrepancies between the simulations and measurements in the allowed band are due to fabrication tolerances. Apart from this, unavoidably, losses are present due to the finite conductance of the metal layers and to the small fractional bandwidth considered, which is only of 2%, according to the measured frequency response. By using only two CSRR stages, the impact upon device miniaturization is important. Indeed, the length of the active device region (that is, excluding access lines) is 14.6 mm. This is more than three times shorter than signal wavelength at the central frequency of the pass band.

In order to demonstrate that it is possible to control the filter bandwidth, we have designed an additional prototype with wider resonant units (stages). Obviously, the resulting bandwidth of the final device (see layout depicted in Fig. 6) is enhanced at the expense of a decrease in frequency selectivity (two stages are also considered in this prototype device). Nevertheless, the frequency selectivity is quite satisfactory, while in-band losses are smaller than in the previous design due to the wider pass band.

4. CONCLUSION

In conclusion, it has been demonstrated that CSRRs, a new type of particle recently proposed by some of the authors, can be applied to the design of narrowband frequency-selective structures in microstrip technology. The combination of these particles, etched in the ground plane, with series capacitive gaps and grounded stubs, leads to highly frequency-selective devices of compact dimensions. The impact of the proposed approach upon miniaturization is evident and, for this reason, the results of this work are patent pending.

ACKNOWLEDGMENTS

This work has been supported by MEC by project contracts TEC2004-04249-C02-01, TEC2004-04249-C02-02, and PROFIT

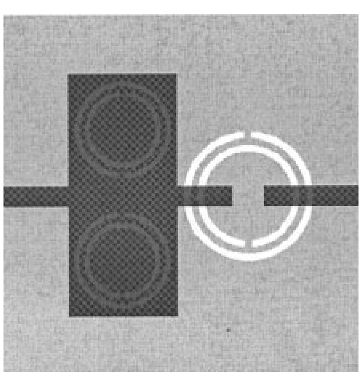

Figure 6 Layout corresponding to the designed CSRRs' microstrip band-pass structure with wider bandwidth. CSRR dimensions are r_{ext} = 2.8 mm, c = 0.29 mm, d = 0.29 mm and r_{ext} = 3.7 mm, c = 0.39 mm, d = 0.39 mm for the wire and gap rings, respectively. Gap spacing is l_g = 1.8 mm and wire dimensions (length and width) are l_w = 14 mm and w_w = 6.2 mm, respectively. Two CSRRs have been included in the input stage in order to obtain wider bandwidth for this resonator cell

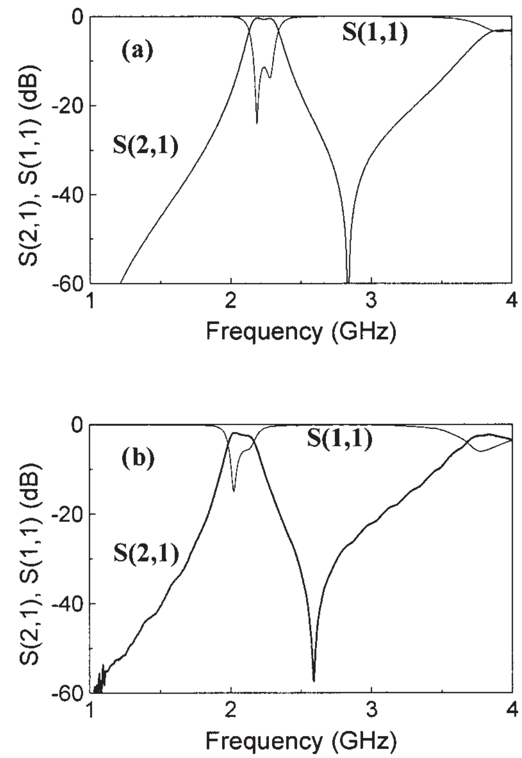

Figure 7 (a) Simulated and (b) measured frequency responses for the device in Fig. 6

330200-2004-113. Thanks also to the European Community (Eureka Program) for the project 2895-TELEMAC. The authors are in debt to R. Pineda (Omicron Circuits s.l.) for the fabrication of the prototypes.

REFERENCES

1. D.R. Smith, W.J. Padilla, D.C. Vier, S.C. Nemat-Nasser, and S. Schultz, Composite medium with simultaneously negative permeability and permittivity, Phys Rev Lett 84 (2000), 4184–4187.
2. V.G. Veselago, The electrodynamics of substances with simultaneously negative values of ε and μ, Sov Phys Usp 10 (1968), 509–514.
3. J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, Magnetism from conductors and enhanced nonlinear phenomena, IEEE Trans Microwave Theory Tech 47 (1999), 2075–2084.
4. R. Marqués, J. Martel, F. Mesa, and F. Medina, Left-handed media simulation and transmission of EM waves in subwavelength SRR-loaded metallic waveguides, Phys Rev Lett 89 (2002), 183901–03.
5. F. Martín, F. Falcone, J. Bonache, R. Marqués, and M. Sorolla, Miniaturized coplanar waveguide stop-band filters based on multiple tuned split-ring resonators, IEEE Microwave Wireless Compon Lett 13 (2003), 511–513.
6. F. Falcone, F. Martín, J. Bonache, R. Marqués, T. Lopetegi, and M. Sorolla, Left-handed coplanar waveguide band-pass filters based on bi-layer split-ring resonators, IEEE Microwave Wireless Compon Lett 14 (2004), 10–12.
7. F. Martín, F. Falcone, J. Bonache, R. Marqués, and M. Sorolla, A new split-ring resonator based left-handed coplanar waveguide, Appl Phys Lett 83 (2003), 4652–4654.
8. F. Falcone, T. Lopetegi, J.D. Baena, R. Marqués, F. Martín, and M. Sorolla, Effective negative-ε stop-band microstrip lines based on complementary split-ring resonators, IEEE Microwave Wireless Compon Lett 14 (2004), 280–282.
9. F. Falcone, T. Lopetegi, M.A.G. Laso, J.D. Baena, J. Bonache, R. Marqués, F. Martín, and M. Sorolla, Babinet principle applied to the

design of metasurfaces and metamaterials, Phys Rev Lett 93 (2004), 197401.

10. A. Grbic and G.V. Eleftheriades, Experimental verification of backward wave radiation from a negative refractive index metamaterial, J Appl Phys 92 (2002), 5930–5935.
11. R. Marqués, F. Mesa, J. Martel, and F. Medina, Comparative analysis of edge and broadside-coupled split-ring resonators for metamaterial design: Theory and experiment, IEEE Trans Antennas Propag 51 (2003), 2572–2581.
12. J.D. Baena, J. Bonache, F. Martín, R. Marqués, F. Falcone, T. Lopetegi, M.A.G. Laso, J. García, I. Gil, and M. Sorolla, Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines, IEEE Trans Microwave Theory Tech (to appear).

AN EFFICIENT METHOD FOR DECREASING THE PROBLEMS OF TRANSMITTER LEAKAGES ON LOW-COST HOMODYNE FMCW RADAR WITH A SIGNAL-ANTENNA CONFIGURATION

Jung Dong Park and Wan Joo Kim
Agency for Defense Development
Yuseong P.O. Box 35-5
Daejeon, 305-600, Republic of Korea

Received 17 February 2005

ABSTRACT: *In this paper, we analyze the effects of IF noise due to transmitter-signal leakage for homodyne frequency-modulated continuous-wave (FMCW) radar with a single-antenna configuration. We find that the magnitude of the IF noise from the front end can be reduced by matching the LO-signal delay time with that of the antenna leakage. As the IF noise has periodic singularities, the spectrum of the IF noise can be modeled by a VCO modulation signal (except low-frequency elements near DC). Based on an analysis of IF noise, we implement a W-band homodyne FMCW radar sensor and the performances are verified outdoors. The presented concept can be applicable to the design of low-cost homodyne FMCW radars with a single-antenna configuration.* © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 46: 512–515, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21032

Key words: *FMCW radar; leakage; single-antenna configuration*

1. INTRODUCTION

Compact frequency-modulated continuous-wave (FMCW) radar has been developed for many applications, such as small industrial-level meters and anticollision radar for vehicles [1, 2]. It utilizes the frequency difference between the transmitted and reflected waves. The frequency of the transmitter signal varies linearly according to the modulation signals. The receptive signal has a time delay $\tau_d = 2R/c$. By mixing the transmitted and reflected signals, the small time difference is replaced by a frequency difference of two signals.

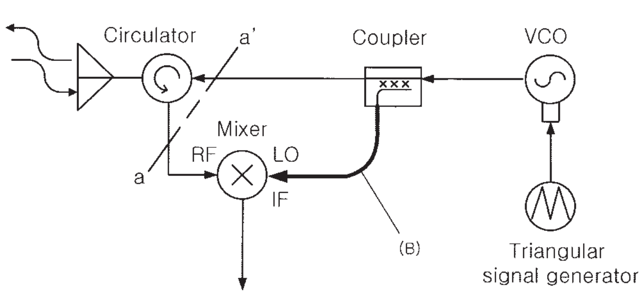

Figure 1 Schematic diagram of an FMCW front end

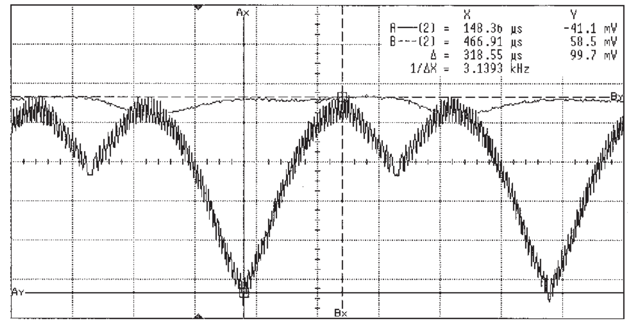

Figure 2 Measured IF output signal of the homodyne FMCW front end

As the signal transmission and reception are simultaneous, it is very difficult to achieve sufficient isolation between the transmitter and receiver. The leakage of the transmitted signal can desensitize the receiver and the beat signals of the valid targets can be swamped with the leakage of the transmitted signal. The main leakage source is known to be the antenna reflection [3].

Several traditional solutions have been used to address these problems. A typical solution is to use a dual-antenna configuration; however, dual antennas increase the cost and size of the radar [4]. Moreover, leakage from the other paths make it difficult to fulfill the required radar sensitivity in some cases. Another way is to use the reflected power canceller (RPC); however, the effectiveness of this method depends on the accuracy with which the amplitude and phase of the leakages can be adjusted [5]. Therefore, those solutions are not proper for small and low-cost industrial-sensor applications. For low-cost radar with a dual-antenna configuration, an FMCW front end with a switching heterodyne receiver has been introduced [6, 7]; however, the heterodyne front end is not effective on an FMCW radar with a single-antenna configuration because the switching receiver cannot separate the target signals from the leakages due to the single-antenna reflection and imperfect circulator isolation.

In this paper, we analyze the IF noise caused by the imperfect separation of receiver and transmitter signal paths in a single-antenna configuration. We propose a solution to improve the effect of the leakage on an FMCW radar. Using the analyzed results, a W-band homodyne FMCW radar with a single-antenna configuration is implemented, measured, and analyzed.

2. ANALYSIS OF THE LEAKAGE NOISE IN THE HOMODYNE FRONT-END

The schematic diagram of a homodyne FMCW radar front end with a single-antenna configuration is shown in Figure 1. The front end presented in this paper has common transmission and reception with a single antenna. A circulator is used to isolate the emission and reception signals. The transmitted signal is frequency modulated with the voltage-controlled oscillator (VCO). The single balanced mixer produces beat signals of the targets by mixing the emission and reception of the modulated signal.

Figure 2 presents a measured IF output signal from the IF port of the mixer. It includes the IF noise due to the transmitter leakages as well as the beat signal. The IF noise has a distinctive shape having periodic singularities at $t = nT_m/2$, with $n = 0, 1, 2, \ldots,$