Bandpass Filters Based on Coupled Split Ring Resonators for Surface Waves on Planar Goubau Lines

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***Abstract*—This paper demonstrates a method for enhancing the performance of recently introduced compact bandpass filters for terahertz surface waves on single wire waveguides, the so-called planar Goubau lines (PGLs). It is firstly shown numerically and validated experimentally that a gapped PGL loaded with a pair of split ring resonators (SRRs) acts as a bandpass filter. The concept and simulation result are validated through experiment. Furthermore, in order to achieve an improved frequency response, a third-order filter based on coupled SRRs is proposed. It is shown that while the size of the proposed filter is further reduced, it additionally benefits from a higher in-band transmission, improved selectivity, and a controllable wide bandwidth.**

***Index Terms*—Metamaterials, terahertz Goubau line, bandpass filter, surface wave.**

I. Introduction

The terahertz band of the electromagnetic spectrum, which bridges the gap between millimeter-wave and infrared bands, is loosely defined between 0.1 THz and 10 THz. Because of the difficulties involved in the generation of terahertz radiation, this part of the spectrum has remained less explored than adjacent bands. However, fostered by the evolution of terahertz sources, there has been in recent years a considerable interest in exploiting this band of the spectrum for numerous potential applications in imaging, medical diagnosis, security screening, and chemical and biological sensing [1]. Furthermore, application for broadband inter-core communications in high data-rate multi-core systems is an attractive potential perspective for terahertz guided waves. In such systems, electronic circuits inside the cores control the transport and storage of electrons, while communication between the different cores at several hundred gigahertz is enabled by inter-core interconnections. Generally, the performance of electronic interconnects is a bottleneck that can limit the data rates of inter-core communications.

Among the terahertz transmission lines that have been proposed in the past, terahertz planar Goubau lines (PGLs) [2] offer wide bandwidth and high data rate, low dispersion, and low loss, thus can be an efficient solution for future broadband on-chip communication [3]. In order to exploit the propagation of surface waves on a PGL in real applications, particularly for future broadband terahertz communications, functional components such as various types of filters, couplers, and power dividers are required. Realizations of metamaterial-inspired bandpass filters for terahertz surface waves on PGL were proposed in [4]. This paper builds on this concept and demonstrates a compact geometry providing increased bandwidth for higher-order bandpass filters.

The rest of the paper is organized as follows. A short introduction on the excitation and propagation of surface waves on PGL is presented in Section II. A first-order bandpass filter based on SRR/gap-loaded PGL is discussed in Section III. Section IV proposes a compact third-order bandpass filter based on coupled SRRs. The section also proposes methods to increase the bandwidth of the proposed filter up to about 39 GHz which is required for the broadband high data-rate on-chip communications. Finally, the main conclusions of the study are highlighted in Section V.

II. Terahertz Surface Waves on Planar Goubau Lines

In 1899, Sommerfeld theoretically investigated the propagation of surface waves along a cylindrical wire of relatively limited conductivity [5]. Efforts towards the physical realization of such line resulted in implementations as wires with modified surface or coated with a dielectric layer. However, as mentioned by Goubau [6], these realizations were based on wires made of good conductors, whereas Sommerfeld's wave exists only for a conductor of finite conductivity. Goubau showed that the required condition for the propagation of surface wave in the interface of a perfect conductor and its surrounding medium is that the structure has a phase velocity which is smaller that the phase velocity of the surrounding medium. Thus, threading the surface of the wire or coating it with a dielectric can be used to satisfy the condition of reduced phase velocity, converting the wire into a surface-wave guide [6]. From this point of view, in the case of the Sommerfeld surface-wave guide the reduction in the phase velocity is achieved by the finite conductivity of the wire.

An important result of using a coated or threaded wire of perfect conductor in a Goubau line is that, unlike in the case of Sommerfeld guides, the surface waves propagating along a

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Goubau line are confined to the wire and the magnitude of the electromagnetic fields exponentially decrease in the transverse plane. Thus, the guided wave has less interactions with the line's environment. Furthermore, the line can be efficiently excited from a coaxial cable by a cone-shape launching device that converts the coaxial mode to Goubau mode [6]–[8].

Recently the propagation of terahertz waves on a single metallic wire with very low attenuation (about 0.03 cm^{-1}) was demonstrated by Wang and Mittleman [9]. This appears as a promising pathway to respond to the need of low-loss and low-dispersion waveguides in the terahertz band. In a more recent work, Akalin et al. [2] have presented a planar version of the line, the so-called planar Goubau line (PGL). The line has attracted increasing interest because of its compatibility with integrated circuit fabrication processes [2], [10]–[14]. The line can be efficiently excited from a coplanar waveguide (CPW) by a launching section which is essentially a CPW with a tapered section that converts the CPW mode to the Goubau mode.

III. Metamaterial-Inspired Bandpass Filter for Planar Goubau Line

In order to exploit the propagation of terahertz waves in real applications, particularly for broadband high data-rate on-chip interconnections, functional components such as various types of filters are required. Different types of terahertz filters based on frequency-selective surfaces, photonic crystals [15]–[17], liquid crystals [18] or metamaterials [12], [19]–[22] have been proposed. However, these filters are exclusively for free-space terahertz waves. Bandstop filters based on corrugated PGL and PGLs loaded with electrical LC resonators have been studied in [23], [24]. In a previous work by the authors it has been demonstrated that since the transverse magnetic fields of the PGL are confined around the line and since they exponentially decay in the transverse plane, a pair of SRRs placed in close proximity to the PGL produces a notch in the transmission spectrum of the PGL [4]. This transmission notch corresponds to the spectrum where the SRR-loaded PGL behaves as a one dimensional medium with negative effective permeability. It has been also shown that this bandstop behavior can be switched to a bandpass behavior by introducing a series capacitive gap to the SRR-loaded PGL [4], [25]–[27]. Figure 1 depicts a microscope image of a fabricated prototype of such a structure. The structure is realized on a 250 μm thick quartz crystal with a relative permittivity $\epsilon_r = 3.78$. The dimensions of the tapered CPW sections , which are used to excite the gapped PGL, are $w = 50$ μm, $w_{\mathrm{gnd}} = 190$ μm, $s_{\mathrm{CPW}} = 5$ μm and $l_1 = 650$ μm [2]. The PGL has a width $w_{\mathrm{G}} = 5$ μm and a total length $l_{\mathrm{G}} = 2100$ μm including the 50 μm gap in the middle. The dimensions of the pair of single split ring resonators are $a = 160$ μm, $b = 130$ μm, $g = 10$ μm and $c = 15$ μm. Fig. 2, depicts the simulated (by means of the Agilent Momentum commercial software [28]) and measured transmission coefficients of the structure. The good agreement between both data sets validate the design approach. Note that about 2 dB of the insertion loss in the passband corresponds to the loss in the launching structures. However, even after excluding the effect of the launching sections, the filter has relatively high insertion loss and poor selectivity. To address these issues, next section is focused on the design of compact third-order bandpass filters with a controllable bandwidth and improved frequency response for terahertz surface waves on PGLs.

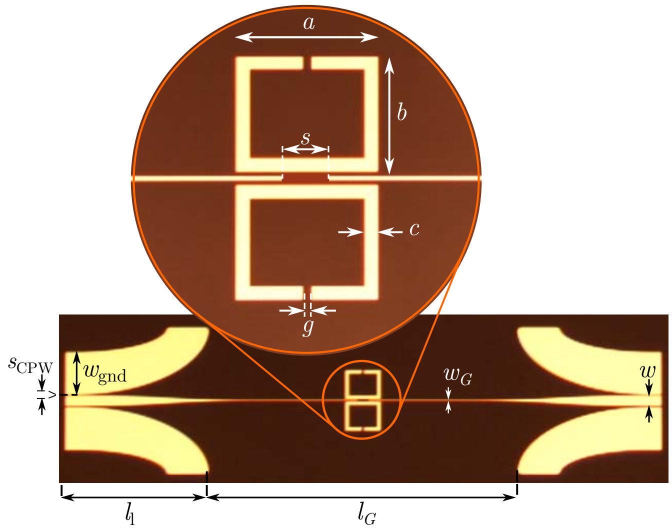

Fig. 1. Microscope photographe of a fabricated prototype of the first order SRR/gap-based bandpass filter for PGL.

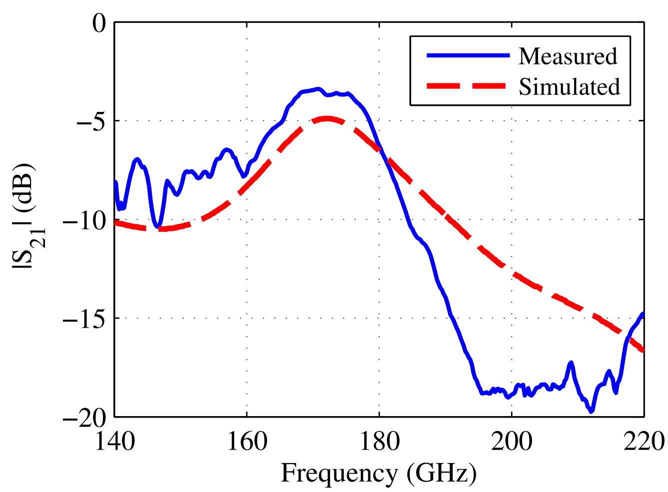

Fig. 2. Comparison between the simulated and measured transmission coefficients of the first order SRR/gap-based bandpass filter of Fig. 1.

IV. Bandpass Filter Based on Coupled Split Ring Resonators

Figure 3 illustrates the layout of the proposed third-order filter, excluding the CPW launching sections. The filter is composed of three coupled double-ring SRRs that are excited by the PGL. In this configuration, the fractional bandwidth (FBW) of the filter is directly proportional to the coupling between the resonators as well as to the coupling between the

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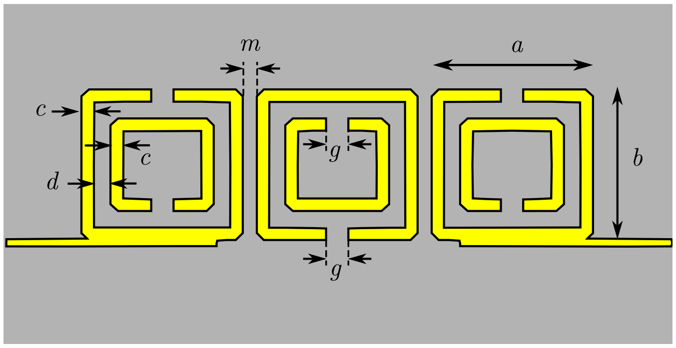

Fig. 3. Layout of the proposed third-order bandpass filter based on the coupled SRRs for terahertz surface waves on PGL.

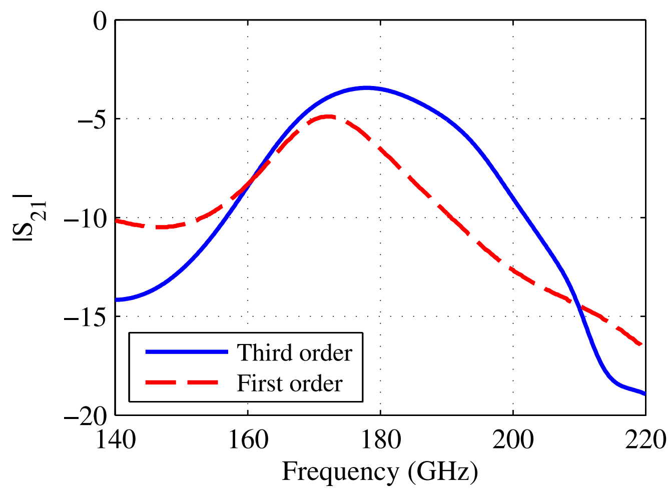

Fig. 4. A comparison between the simulated transmission coefficients of the first-order filter of Fig.1 and the proposed third-order filter of Fig. 3.

PGL sections and the first and the last resonator [29], [30]. Thus, in order to achieve a wideband filter with improved in-band transmission, the coupling between the PGL sections and the SRRs should be maximized. To this end, in this design the PGL sections are directly connected to the first and last SRRs. Furthermore, the strongest coupling between the SRRs can be achieved through mixed electric and magnetic coupling of the SRRs. This is achieved by orienting the coupled SRRs in opposite directions [30]. The dimensions of the SRRs are as follows: $a = 140\ \mu\text{m}$, $b = 130\ \mu\text{m}$, $d = 15\ \mu\text{m}$, $c = 10\ \mu\text{m}$, $g = 20\ \mu\text{m}$, and the space between SRRs is $m = 11\ \mu\text{m}$. The filter is as compact as $0.4\lambda_g \times 0.13\lambda_g$, where λ_g is the guided wavelength at the filters center frequency.

Figure 4 depicts a comparison between the simulated transmission coefficients of the first-order filter of the previous section and the proposed third-order filter of Fig. 3. The figure shows that the proposed third-order filter benefits form a wider bandwidth, higher in-band transmission and improved out-of-band response.

The filter's bandwidth can be further increased by increasing the SRR-to-SRR couplings through decreasing the space m between the SRRs. Figure 5 shows the filter's frequency

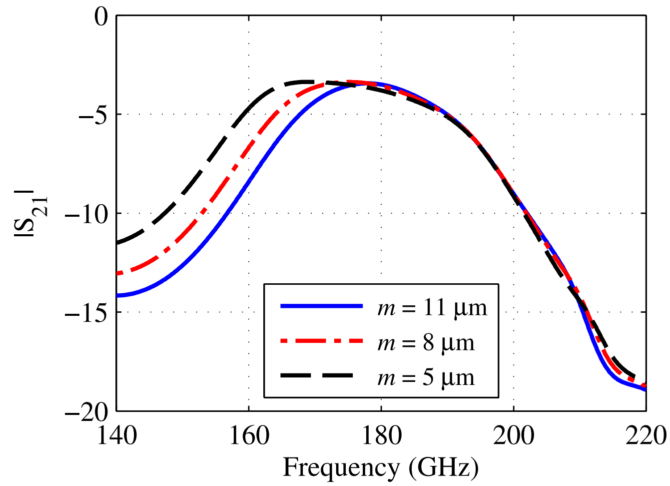

Fig. 5. Simulated transmission coefficient of the third-order filter of Fig. 3 for three different values of the inter-SRR spacing $m = 5\ \mu\text{m}, 8\ \mu\text{m}$ and $11\ \mu\text{m}$.

response for three different values of the inter-SRR spacing $m = 5\ \mu\text{m}, 8\ \mu\text{m}$ and $11\ \mu\text{m}$. The figure shows that while the filter's bandwidth is about 30 GHz for $m = 11\ \mu\text{m}$, decreasing the SRR-to-SRR spacing to $m = 5\ \mu\text{m}$ results in a bandwidth increase to 39 GHz, which corresponds to a 30% wider bandwidth.

V. Conclusion

Application of SRRs for the realization of bandpass filters for the terahertz surface waves on PGL has been illustrated in this paper. It has been first shown numerically and experimentally that an SRR/gap-loaded PGL can be used as a building block for bandpass filters for terahertz surface waves. On this basis, a third-order filter based on coupled SRRs has been then proposed, and it has been shown how compactness and bandwidth can be enhanced by controlling coupling between the SRRs. As a result, the designed third-order filter is compact ($0.4\lambda_g \times 0.13\lambda_g$, λ_g being the guided wavelength at the filters center frequency), it offers good in-band transmission, out-of-band rejection, and a controllable bandwidth.

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References

[1] W. Withayachumnankul, G. M. Png, X. Yin, S. Atakaramians, I. Jones, H. Lin, B. S. Y. Ung, J. Balakrishnan, B. W.-H. Ng, B. Ferguson, S. P. Mickan, B. M. Fischer, and D. Abbott, "T-ray sensing and imaging," *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1528–1558, Aug. 2003.

[2] T. Akalin, A. Treizebré, and B. Bocquet, "Single-wire transmission lines at terahertz frequencies," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 6, pp. 2762–2767, 2006.

[3] K. Ohashi, K. Nishi, T. Shimizu, M. Nakada, J. Fujikata, J. Ushida, S. Torii, K. Nose, M. Mizuno, H. Yukawa, M. Kinoshita, N. Suzuki, A. Gomyo, T. Ishi, D. Okamoto, K. Furue, T. Ueno, T. Tsuchizawa, T. Watanabe, K. Yamada, S.-I. Itabashi, and J. Akedo, "On-chip optical interconnect," *Proceedings of the IEEE*, vol. 97, no. 7, pp. 1186–1198, Jul. 2009.

[4] A. K. Horestani, W. Withayachumnankul, A. Chahadih, A. Ghaddar, M. Zehar, D. Abbott, C. Fumeaux, and T. Akalin, "Metamaterial-Inspired Bandpass Filters for Terahertz Surface Waves on Goubau Lines," *IEEE Transactions on Terahertz Science and Technology,* accepted .

[5] A. Sommerfeld, "Ueber die Fortpflanzung elektrodynamischer Wellen längs eines Drahtes," *Annalen der Physik*, vol. 67, no. 233-290, Mar. 1899.

[6] G. Goubau, "Surface waves and their application to transmission lines," *Journal of Applied Physics*, vol. 21, no. 11, p. 1119, 1950.

[7] ——, "Open wire lines," *IRE Transactions on Microwave Theory and Techniques*, vol. 39, pp. 6–9, 1956.

[8] M. King and J. Wiltse, "Surface-wave propagation on coated or uncoated metal wires at millimeter wavelengths," *IRE Transactions on Antennas and Propagation*, vol. 10, no. 3, pp. 246–254, 1962.

[9] K. Wang and D. Mittleman, "Metal wires for terahertz wave guiding," *Nature*, vol. 432, no. 7015, pp. 376–379, 2004.

[10] T. Akalin, J. Lampin, L. Desplanque, E. Peytavit, and A. Treizebré, "Propagation of terahertz pulses along planar Goubau lines," in *Proc. IEEE Joint 31st International Conference on Infrared Millimeter Waves and 14th International Conference on Teraherz Electronics*, Sep. 2006, pp. 568–568.

[11] Y. Xu and R. Bosisio, "A comprehensive study on the planar type of Goubau line for millimetre and submillimetre wave integrated circuits," *IET Microwaves, Antennas & Propagation*, vol. 1, no. 3, pp. 681–687, 2007.

[12] L. Si, Y. Yuan, H. Sun, and X. Lv, "Characterization and application of planar terahertz narrow bandpass filter with metamaterial resonators," *2008 International Workshop on Metamaterials*, pp. 351–354, Nov. 2008.

[13] T. Akalin, E. Peytavit, and J.-F. Lampin, "THz long range plasmonic waveguide in membrane topology," in *Proc. IEEE 33rd International Conference on Infrared, Millimeter and Terahertz Waves*, Sep. 2008, pp. 106–107.

[14] Y. Xu, C. Nerguizian, and R. Bosisio, "Wideband planar Goubau line integrated circuit components at millimetre waves," *IET Microwaves, Antennas & Propagation*, vol. 5, no. 8, p. 882, 2011.

[15] H. Němec, L. Duvillaret, F. Garet, P. Kužel, P. Xavier, J. Richard, and D. Rauly, "Thermally tunable filter for terahertz range based on a one-dimensional photonic crystal with a defect," *Journal of Applied Physics*, vol. 96, no. 8, pp. 4072–4075, 2004.

[16] W. Withayachumnankul, B. M. Fischer, and D. Abbott, "Quarter-wavelength multilayer interference filter for terahertz waves," *Optics Communications*, vol. 281, no. 9, pp. 2374–2379, May 2008.

[17] J. Li, "Terahertz wave narrow bandpass filter based on photonic crystal," *Optics Communications*, vol. 283, no. 13, pp. 2647–2650, Jul. 2010.

[18] C.-Y. Chen, C.-L. Pan, C.-F. Hsieh, Y.-F. Lin, and R.-P. Pan, "Liquid-crystal-based terahertz tunable Lyot filter," *Applied Physics Letters*, vol. 88, no. 10, p. 101107, 2006.

[19] W. Withayachumnankul and D. Abbott, "Metamaterials in the terahertz regime," *IEEE Photonics Journal*, vol. 1, no. 2, pp. 99–118, Aug. 2009.

[20] M. Lu, W. Li, and E. Brown, "Second-order bandpass terahertz filter achieved by multilayer complementary metamaterial structures," *Optics Letters*, vol. 36, no. 7, pp. 1071–1073, Apr. 2011.

[21] Y. Zhu, S. Vegesna, V. Kuryatkov, M. Holtz, M. Saed, and A. A. Bernussi, "Terahertz bandpass filters using double-stacked metamaterial layers." *Optics Letters*, vol. 37, no. 3, pp. 296–298, Feb. 2012.

[22] L. Liang, B. Jin, J. Wu, Y. Huang, Z. Ye, X. Huang, D. Zhou, G. Wang, X. Jia, H. Lu, L. Kang, W. Xu, J. Chen, and P. Wu, "A flexible wideband bandpass terahertz filter using multi-layer metamaterials," *Applied Physics B*, May 2013.

[23] T. Akalin, E. Peytavit, and J. Lampin, "Bendings and filters with single strip THz plasmonic waveguides," *Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz Electronics. IRMMW-THz*, pp. 75–76, 2007.

[24] W.-C. Chen, J. J. Mock, D. R. Smith, T. Akalin, and W. J. Padilla, "Controlling gigahertz and terahertz surface electromagnetic waves with metamaterial resonators," *Physical Review X*, vol. 1, no. 2, p. 021016, Dec. 2011.

[25] F. Martín, J. Bonache, F. Falcone, M. Sorolla, and R. Marqués, "Split ring resonator-based left-handed coplanar waveguide," *Applied Physics Letters*, vol. 83, no. 22, pp. 4652–4654, Dec. 2003.

[26] F. Falcone, F. Martín, J. Bonache, M. A. G. Laso, J. García-García, J. D. Baena, R. Marqués, and M. Sorolla, "Stop-band and band-pass characteristics in coplanar waveguides coupled to spiral resonators," *Microwave and Optical Technology Letters*, vol. 42, no. 5, pp. 386–388, Sep. 2004.

[27] J. Bonache, F. Martín, F. Falcone, J. García, I. Gil, T. Lopetegi, M. A. G. Laso, R. Marqués, F. Medina, and M. Sorolla, "Super compact split ring resonators CPW band pass filters," in *Proc. IEEE MTT-S International Microwave Symposium Digest*, vol. 3, 2004, pp. 1483–1486.

[28] "Advanced Design System (ADS)," 2011.

[29] J. S. Hong and M. J. Lancaster, "Couplings of microstrip square open-loop resonators for cross-coupled planar microwave filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 44, no. 12, pp. 2099–2109, 1996.

[30] ——, *Microstrip Filters for RF/Microwave Applications*. New York: Wiley, 2001.

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