Miniaturized and Harmonic-Suppressed Rat-Race Couplers Based on Slow-Wave Transmission Lines

Jordi Selga[1], Jan Coromina[1*], Paris Vélez[1], Armando Fernández-Prieto[2], Jordi Bonache[1], Ferran Martín[1]

[1] CIMITEC, Departament d'Enginyeria Electrònica, Universitat de Barcelona, 08193 Bellaterra, Spain
[2] Departamento de Electrónica y Electromagnetismo, Universidad de Sevilla, 41012 Sevilla, Spain
[*]jan.coromina@uab.cat

Abstract: In this paper, a compact rat-race hybrid coupler with harmonic suppression based on slow-wave transmission lines (SW-TL) is presented. Such artificial lines are implemented by periodic loading a host microstrip line with series meandered inductors and shunt patch capacitors. The presence of both loading elements has a twofold effect, i.e., phase velocity reduction (due to the enhancement of the effective inductance and capacitance of the periodic line), and the generation of a controllable stop band in the frequency response (due to the Bragg effect, inherent to periodicity). It is shown that by designing the unit cell of the periodic line with an electrical length of 45°, at least the first five harmonic bands of the rat-race coupler are efficiently suppressed, keeping the band of interest unaltered. Moreover, 82% size reduction, as compared to the ordinary coupler, is achieved in the reported SW-TL-based prototype.

1. Introduction

Size reduction and spurious/harmonic suppression have been (and are still) two challenges in the design of distributed microwave components. Miniaturization is of special interest in device topologies involving multiple transmission line sections, such as high-order filters or couplers, among others. Spurious and harmonic bands are inherent to distributed components, and may be the cause of interferences or undesired signals that may degrade system functionality. Therefore, the suppression of such bands is a due in certain applications, and achieving that purpose without the penalty of increasing circuit size is of the highest interest.

Slow-wave transmission lines (SW-TL) based on periodic structures are good candidates to simultaneously reduce circuit size and reject spurious/harmonic bands [1]-[3]. In such artificial lines, the phase velocity is smaller than the one of their ordinary counterparts implemented on the same substrate. Therefore, signal wavelengths are reduced, with direct impact on circuit compactness. Moreover, due to the Bragg effect, related to periodicity, periodic SW-TLs exhibit stop bands at controllable frequencies, useful for spurious/harmonic suppression.

Most periodic SW-TLs are either based on capacitive [4]-[15] or inductive [16]-[19] loading, and few of them are implemented by combining both reactive elements [20]-[23] (other SW-TLs loaded with distributed elements or combinations of distributed/semi-lumped components have been also reported [24]-[30]). The advantage of simultaneous inductive and capacitive (LC) loading is major design flexibility and the possibility to achieve further levels of miniaturization, as compared to SW-TLs based on a single reactive element. In [23], a compact and harmonic suppressed branch-line coupler based on LC-loaded SW-TLs was reported. There are many papers in the recent literature devoted to the miniaturization and harmonic suppression of branch line couplers [9],[12],[24]-[39]. Among them, the devices presented in [31],[33],[35],[38] use either capacitive or both capacitive and inductive loading, whereas the papers [25],[27] present branch-line couplers with size reduction based on T-shaped structures. However, fewer efforts have been dedicated to achieve that objective in rat-race couplers [9],[29],[40]-[48]. In [24],[26],[29],[45], miniaturization in the considered couplers is achieved by means of open-stub loaded lines. In [43],[47], the authors use optimization techniques (based on space mapping) for the implementation of harmonic suppressed rat-race couplers based on semi-lumped elements. In the works [44],[48], the authors use fractal and T-shaped structures, respectively. Finally, in [40]-[42],[46], the capacitive or capacitive/inductive loaded lines are used to reduce the size of the proposed couplers. In this paper, based on the periodic LC-loaded SW-TLs first proposed in [49], we report a miniature rat-race hybrid coupler able to suppress at least up to the fifth harmonic band. As compared to previous works devoted to size reduction and harmonic suppression of rat-race couplers, in this paper we report a design methodology based on the Floquet analysis of periodic structures, and we justify the convenience to use unit cells with a specific electrical length (to be discussed later) in order to efficiently suppress the harmonic bands leaving the band of interest unaltered.

2. SW-TLs with LC loading and design equations

The circuit schematic and topology of the considered LC-loaded SW-TLs are depicted in Fig. 1, where k, l and Z_0 are the phase constant, length and characteristic impedance, respectively, of the host line, and the loading reactive elements are designated by L_{ls} and C_{ls}. The dispersion relation (neglecting losses) in the regions of propagation and the characteristic (Bloch) impedance of such lines are given by the following equations [2],[50]

$$\cos(\beta l) = A \tag{1}$$

$$Z_B = \frac{-jB}{\sin(\beta l)} \equiv \frac{B'}{\sin(\beta l)} \tag{2}$$

with

$$A=\cos(kl)-\left(\frac{L_{ls}}{2Z_0}+\frac{C_{ls}Z_0}{2}\right)\omega\sin(kl)-$$
$$-\frac{L_{ls}C_{ls}}{2}\omega^2\cos^2(kl/2) \quad (3)$$

$$B'=L_{ls}\omega\cos(kl)+\left(Z_0-\frac{L_{ls}^2\omega^2}{4Z_0}-\frac{L_{ls}C_{ls}\omega^2 Z_0}{2}\right)\sin(kl)-$$
$$-C_{ls}\omega Z_0^2\sin^2(kl/2)-\frac{L_{ls}^2C_{ls}\omega^3}{4}\cos^2(kl/2) \quad (4)$$

In (1), β is the phase constant of the loaded line, and A and B appearing in (1) and (2), respectively, are the first row elements of the transmission *ABCD* matrix of the unit cell.

The design specifications in the SW-TL are the electrical length of the unit cell, βl, and the characteristic impedance, Z_B, at the design frequency, f_0. The electrical length of the unit cell is dictated by the number of considered cells, N, and by the required phase, θ, of the whole SW-TL under consideration, that is, $\beta l=\theta/N$. To determine N, or βl, it should be taken into account that the onset of the first stop band of the periodic structure, f_C, is intimately related to βl (which can only take discrete values as long as N is an integer and θ is a design specification). Obtaining the analytical dependence of f_C on βl from (3) is not possible. However, a rough approximation can be inferred from the lumped element equivalent circuit model of the unit cell, with the transmission line sections replaced with a shunt capacitor, C, in parallel with C_{ls}, and with a pair of series inductors, $L/2$,

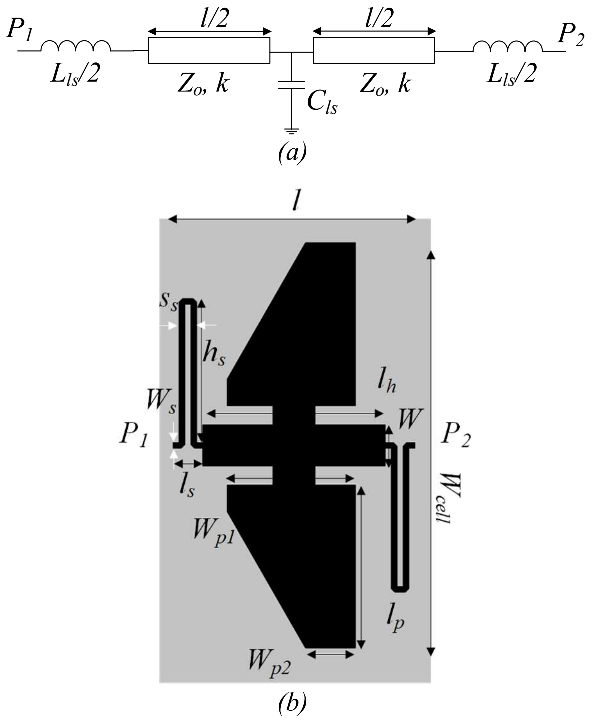


Fig. 1. *Circuit schematic (a) and topology (b) of the SW-TL (unit cell) based on simultaneous inductive and capacitive loading. The (roughly) triangular shape of the capacitor patches is considered in order to accommodate such patches in the inner region of the coupler (see Fig. 3).*

series connected to the loading inductances $L_{ls}/2$. For such circuit model, the cutoff frequency is found to be [2],[15]

$$f_C=\frac{1}{\pi\sqrt{(L+L_{ls})(C+C_{ls})}} \quad (5)$$

whereas the electrical length of the unit cell can be expressed as

$$\beta l=\frac{\theta}{N}=2\pi f_0\sqrt{(L+L_{ls})(C+C_{ls})} \quad (6)$$

Therefore, the ratio between f_C and f_0 is

$$\frac{f_C}{f_0}=\frac{2N}{\theta}=\frac{2}{\beta l} \quad (7)$$

The shorter transmission line sections of the rat-race coupler have a phase of $\theta=\pi/2$. Therefore, the considered values of the unit cell electrical length must satisfy $\beta l=\pi/2N$. In order to suppress the first harmonic of the coupler, at $3f_0$, the following condition must be satisfied: $f_C/f_0<3$. This means that either $\beta l=\pi/2$ ($N=1$), or $\beta l=\pi/4$ ($N=2$). However, $\beta l=\pi/4$ is preferred for two main reasons: (i) f_C is further away from f_0 (consequently preserving the coupler response in the region of interest), and (ii) the stop band is extended up to higher frequencies (thus enhancing the harmonic suppression capability of the coupler). Thus, we can conclude that the coupler will consist of three quarter wavelength ($\theta=\pi/2$) SW-TL sections (each one with $N=2$) and one SW-TL section with $\theta=3\pi/2$ (and $N=6$).

Besides (1) and (2), an additional design equation is the slow wave ratio

$$swr=\frac{v_{pL}}{v_{po}}=\frac{\omega/\beta}{\omega/k}=\frac{kl}{\beta l}\ , \quad (8)$$

which provides the level of miniaturization (in length) of the SW-TL. In (8), v_{pl} and v_{po} are the phase velocities of the loaded and unloaded lines.

3. Rat-race coupler design

The design process of the rat-race coupler consists of the following steps:

1) In the first step, the topology of the unit cell, i.e., the one of Fig. 1 (a), described to a good approximation in the region of interest by the circuit model, also shown in Fig. 1 (b), is introduced, and the operating frequency, f_0, is set to a certain value (dictated by specifications).

2) From the value of *swr* (a design parameter determining the length reduction of the unit cell), the characteristic impedance Z_B (determined by the specific application, and equal to Z_B = 70.71 Ω in a rat-race hybrid coupler), and the required electrical length of the unit cell (βl = 45º in our case), we calculate the element parameters of the schematic of Fig. 1(a), that is, L_{ls}, C_{ls}, Z_0 and kl. Concerning kl, it is directly determined from equation (8), provided *swr* is set to a certain value and βl is an input parameter (βl = 45º in our case). For the determination of Z_0, C_{ls} and L_{ls}, there is some freedom as long as these three parameters are given by two equations (i.e., equations 1 and 2). The constrains are related to the fact that extreme values of C_{ls} and L_{ls} must be avoided since then these elements must be implemented in planar form, as quasi-lumped elements. Therefore, these elements are determined from an iterative process, where Z_0 is first set to a value equal to Z_B, and L_{ls} and Lare univocally obtained from (1) and (2). Then, the layout of these elements is inferred from Keysight Momentum, where the dimensions are optimized in order to obtain the required reactances at the design frequency. Once these layouts are obtained, it is determined if the lateral dimensions of both the meander and the patch are comparable or are very different. In the second case, Z_0 is varied in order to compensate the lateral size difference between the quasi-lumped reactive elements, taking into account that an increase of Z_0 increases C_{ls} and decreases L_{ls}, and vice versa.

3) In the third step, once Z_0, L_{ls} and C_{ls} have been determined, the individual layouts of the meander, patch and line are assembled, and it is verified if the design goals are satisfied (i.e., if Z_B and βl inferred from electromagnetic simulation satisfy the requirements), and the complete layout of the unit cell is optimized if necessary. Note that the length reduction factor cannot exactly coincide with the one given by the selected value of *swr*, since the meander and the patch have finite dimensions.

4) In the next step, the complete circuit layout is assembled, and the topology of the patches is somehow modified, if necessary, to accommodate half of the patches in the inner region of the coupler (note that each capacitance C_{ls} is implemented by means of two parallel patches in order to avoid an excessive patch size).

5) Finally, the electromagnetic simulation of the whole structure is carried out, and it is optimized again if necessary.

The operating frequency of the designed coupler has been set to $f_0 = 0.825$ GHz (central frequency of the E-UTRA Band 20 for LTE). For a rat-race coupler with equal power division between the output ports (hybrid coupler), the characteristic impedance of the constitutive lines should be $Z_B = 70.71\ \Omega$. By considering a slow wave ratio of $swr = 0.25$, and taking into account that the electrical length of the unit cell should be set to $\beta l = \pi/4$ (for the reasons explained before), it follows (using 8) that $kl = \pi/16$. Following the previous design procedure, the impedance of the host line and the reactive elements have been found to be $Z_0 = 80\ \Omega$, $L_{ls} = 8.251$ nH and $C_{ls} = 1.471$ pF. From these values, we have generated the layout of the unit cell [Fig. 1(b)], by implementing the loading inductances and capacitances by means of meander inductors and (roughly) triangular patch capacitor, respectively. The topologies of the meander and patch, as well as the whole topology of the unit cell, have been optimized by means of the *Keysight Momentum* commercial software, as indicated before.

The dependence of the electrical length of the unit cell and characteristic impedance with frequency is depicted in Fig. 2, where it can be seen that the required values at f_0 are obtained to a very good approximation. It should be mentioned that the unconventional shape of the patches is justified by the need to accommodate such patches in the inner region of the rat-race topology, shown in Fig. 3(a). The photograph of the fabricated device is depicted in Fig. 3(b). The size of the coupler is only 18% the size of the ordinary counterpart.

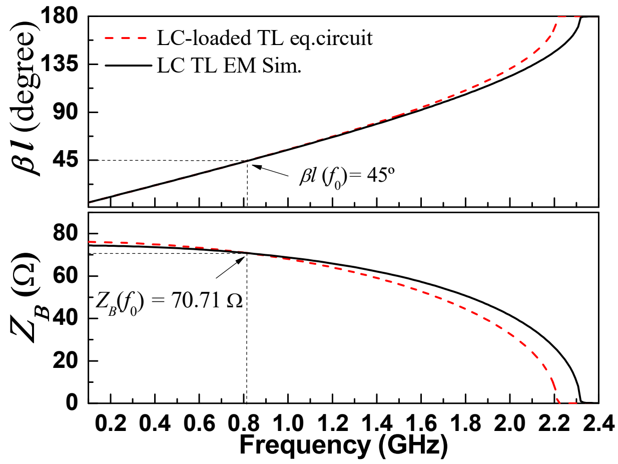
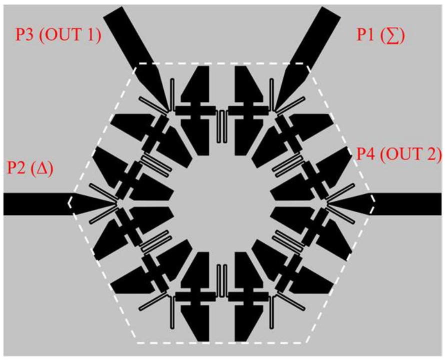
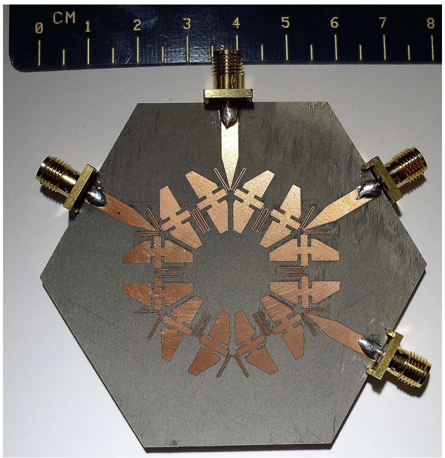


Fig. 2. *Dependence of βl and Z_B with frequency. The considered substrate is the Rogers RO4003C with dielectric constant $\varepsilon_r = 3.55$, thickness $h = 1.524$ mm and loss tangent $\tan\delta = 0.0022$. Unit cell dimensions are indicated in the caption of Fig. 3.*



(a)



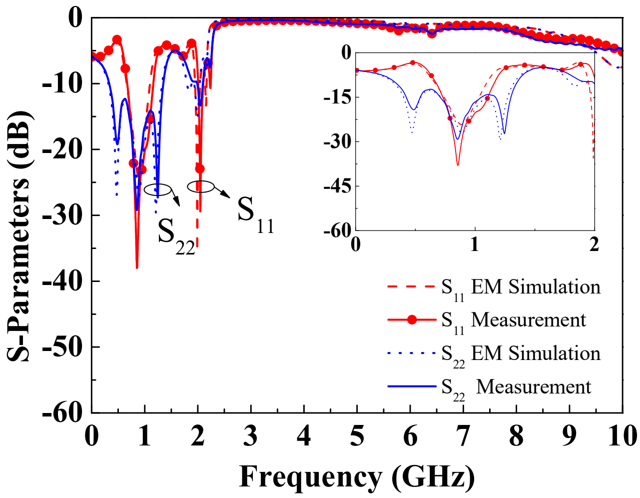
(b)

Fig. 3. *Layout (a) and photograph (b) of the designed SW-TL coupler. The dimensions, in reference to Fig. 1, are: $W = 1.40$ mm, $l_h = 6.18$ mm, $l_p = 5.52$ mm, $W_{p1} = 4.34$ mm, $W_{p2} = 1.70$ mm, $S_s = 0.60$ mm, $h_s = 4.865$ mm, $l_s = 1$ mm, $W_s = 0.20$ mm, $W_{cell} = 13.70$ mm, $l = 8.18$ mm. The access lines have a width of 3.36 mm, corresponding to 50 Ω characteristic impedance. The area of the indicated (dashed-line) hexagon is 1544 mm^2 (whereas the area of the conventional coupler is 8590 mm^2).*

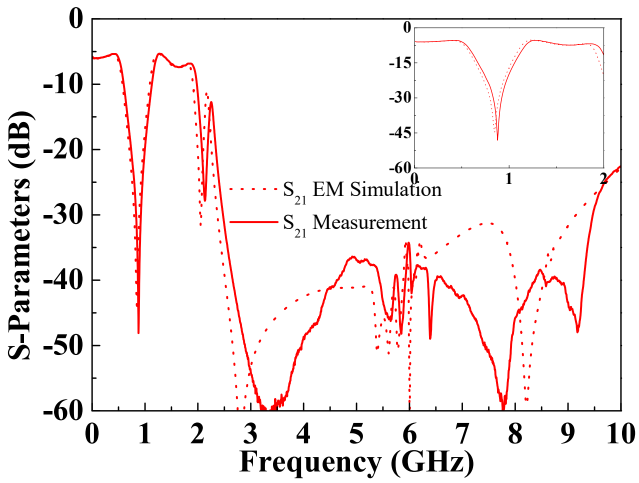
4. Results and comparison to other compact couplers

The response of the coupler (including the lossy electromagnetic simulation and measurement) is depicted in Fig. 4. The measurements have been carried out by means of the 4-port *Agilent PNA N5221A* network analyzer, and calibration has been done using an electronic calibration (*Ecal Module N7554A*). The proposed coupler exhibits a high harmonic rejection efficiency, with more than 17 dB suppression up to at least 10 GHz (which means that at least the first five harmonics are strongly suppressed). The phase balance for the Σ and Δ ports in the vicinity of f_0, depicted in Fig. 5, also validates the coupler functionality in the region of interest.

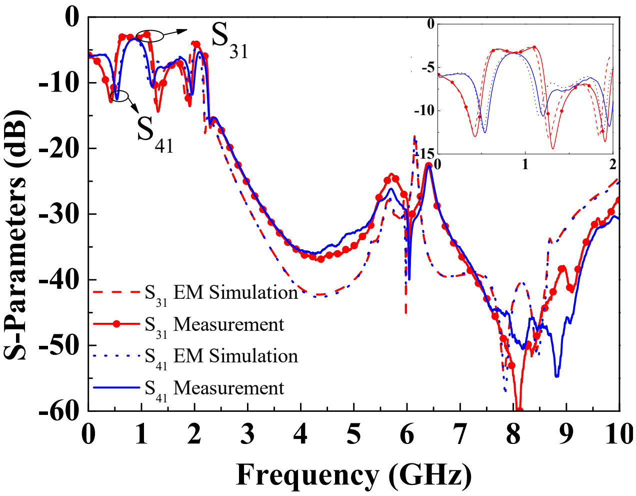
The simulated response of the ordinary coupler, designed at the same frequency and considering identical substrate, is compared to the simulated response of the designed SW-TL-based coupler in Fig. 6. It can be appreciated that the response of the SW-TL-based coupler is roughly indistinguishable from the one of the ordinary coupler in the region of interest (i.e., around f_0), which means that the functionality of the coupler in such region is compatible with the elimination of harmonic bands and with a substantial size reduction.



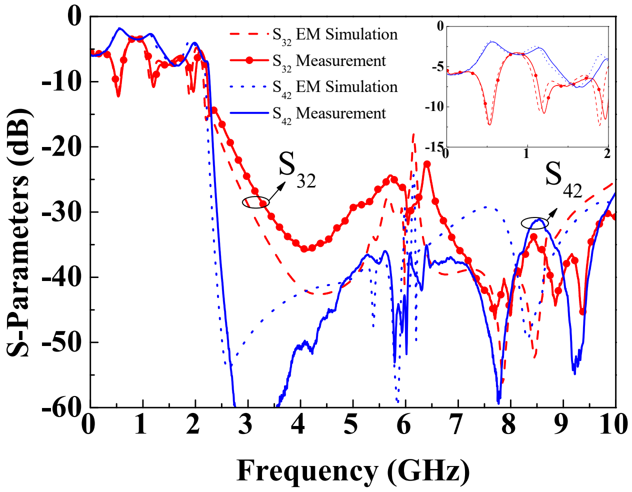
(a)



(b)

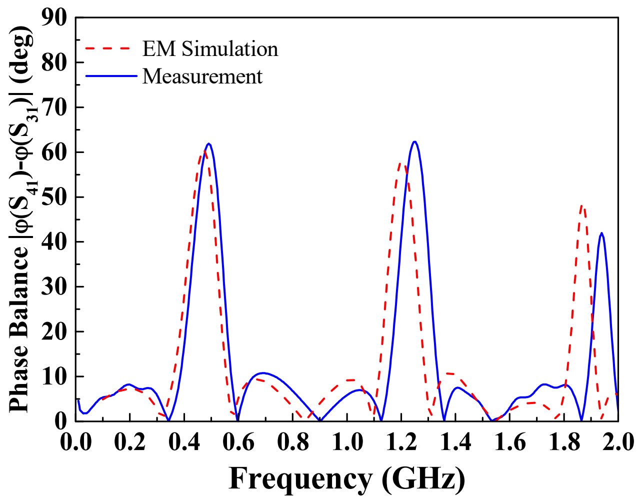


(c)

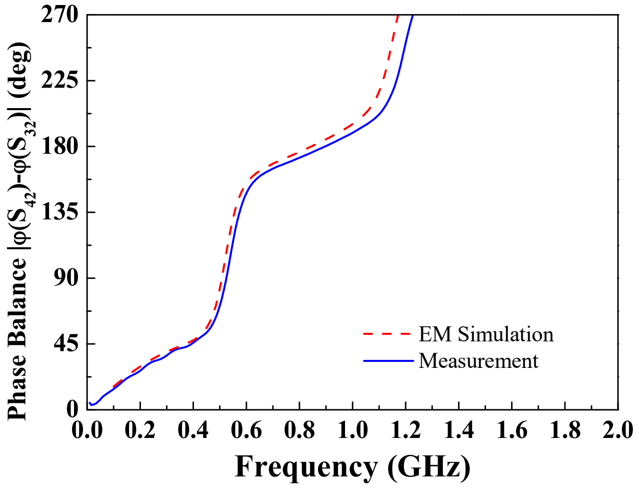


(d)

Fig. 4. *Response of the designed and fabricated SW-TL-based rat-race coupler. (a) Matching from ports 1 (Σ-port) and 2 (Δ-port); (b) isolation between ports 1 and 2; (c) power division from port 1; (d) power division from port (2). Zoom views are shown in the insets.*



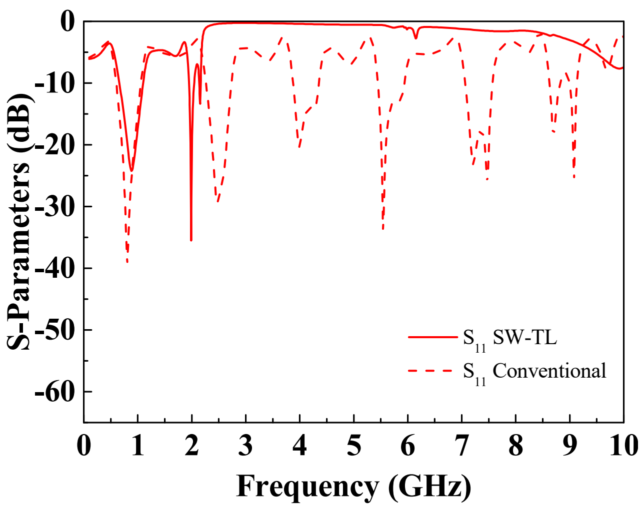
(a)



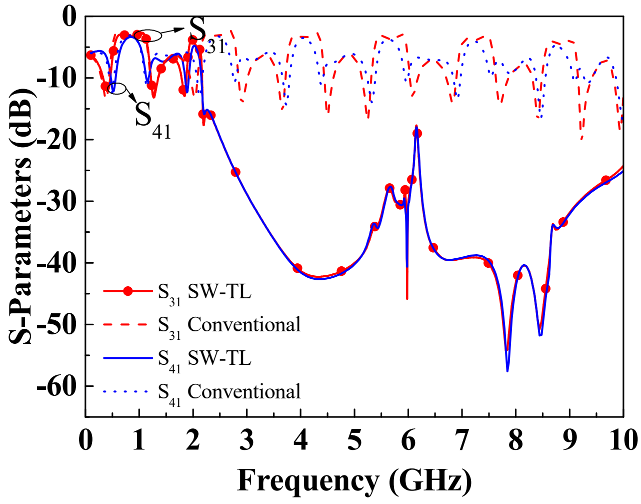
(b)

Fig. 5. *Phase balance for the Σ (a) and Δ (b) ports.*

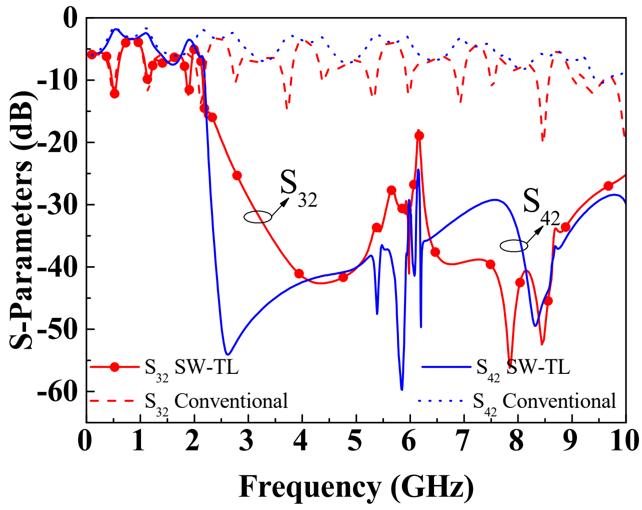
To demonstrate the validity of the circuit schematic of Fig. 1(a) in the region of interest, the lossless electromagnetic simulation of the designed coupler of Fig. 3(a) (inferred from *Keysight Momentum*) is compared to the circuit simulation (obtained from the schematic simulator of *Keysight ADS*) in Fig. 7. Note that for a proper comparison, losses have been excluded in the electromagnetic simulation (in coherence with the schematic model, where losses are not present). In spite of the relative complexity of the considered device (with 12 unit cells), the agreement between the circuit and electromagnetic simulation is good. Consequently, the circuit model and the design procedure of the coupler, detailed in the previous section, are validated. It should be mentioned that the validity of the model is restricted to the frequency region where the meanders and patches are adequately described by an inductance and a capacitance, respectively. For that reason, the comparison is limited to 2.5 GHz in Fig. 7.



(a)

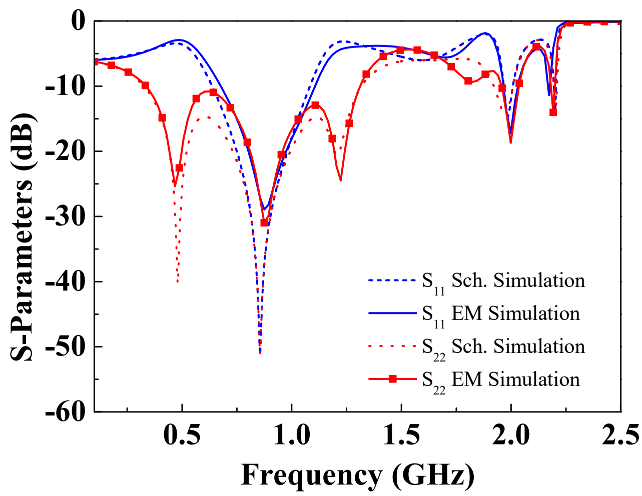


(b)

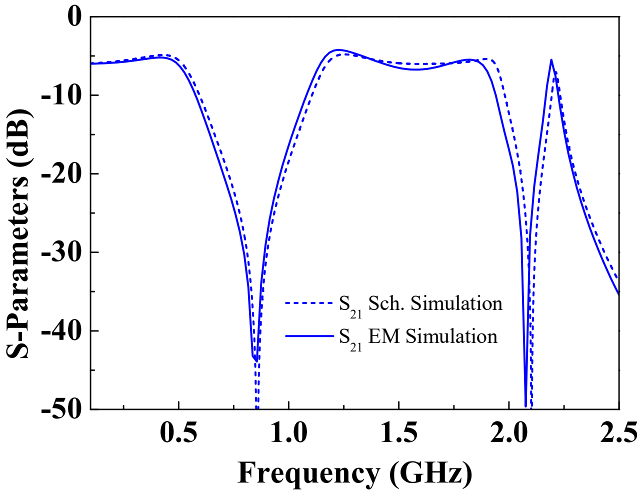


(c)

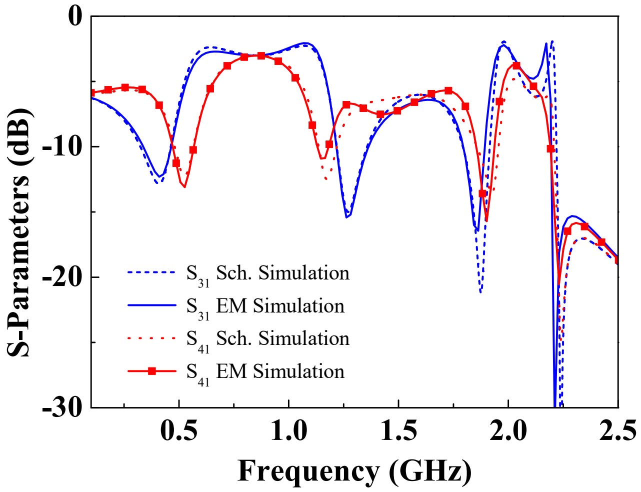
Fig. 6. *Comparison of the responses of the ordinary and SW-TL-based couplers. Only the matching from port 1 (a), and power division from ports 1 (b) and 2 (c) are included.*



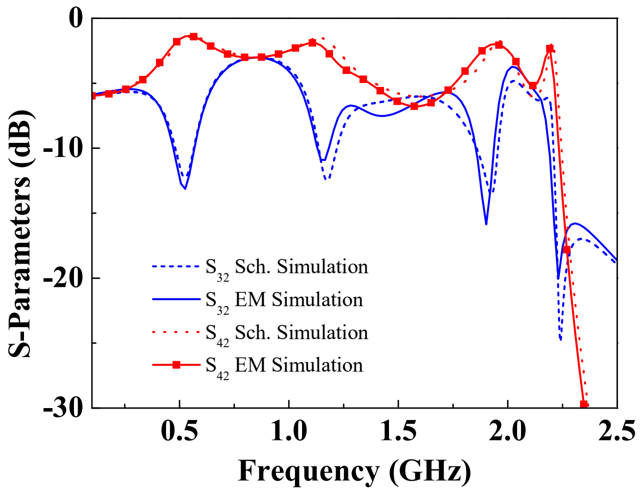
(a)



(b)



(c)



(d)

Fig. 7. *Comparison of the lossless coupler response inferred from circuit and electromagnetic simulation in the region of interest. (a) Matching from ports 1 (Σ-port) and 2 (Δ-port); (b) isolation between ports 1 and 2; (c) power division from port 1; (d) power division from port (2).*

The proposed SW-TL-based coupler is compared to other compact couplers in Table 1 (the relative size is in comparison to the size of the ordinary coupler) and in Table 2. The couplers of refs. [41], [42] and [48] are extremely small, but their harmonic suppression capability is very limited or null. The coupler presented in [43] exhibits a very good combination of size reduction and harmonic suppression, with only 15% the size of the ordinary counterpart, and suppression up to the 6th harmonic. In the coupler presented in this work, the size reduction is comparable (18%) to the one in [43], and up to the 5th harmonic is suppressed. However, it is remarkable that in the present work the overall harmonic suppression level of the coupler is better than the one found in [43]. Therefore, the proposed SW-TL-based coupler, implemented by artificial lines with simultaneous inductive and capacitive loading, is found to be competitive in terms of combination of size and harmonic suppression. Moreover, it has been clearly pointed out that the electrical length of the unit cell of the considered periodic lines should not be arbitrary. Particularly, it has been found that unit cells with 45º electrical length are required to maintain the coupler response in the region of interest unaltered and maximize the stopband for harmonic suppression.

Concerning the useful operating range of the coupler, this is given by the bandwidth. Also in Table 1, we have included the bandwidth for S_{11}, defined (in this work) as the frequency band where matching is better than −15 dB, the bandwidth for power splitting, where the response deviates no more than ± 0.25 dB from the value at f_0, and the bandwidth for phase balance (in this case with a tolerance of ± 5º). The previous bandwidths are compared to those of the other couplers, and we can conclude that the proposed coupler is also competitive in this regard.

To end this section, let us justify the reason for using periodic structures, rather than a filtering non-periodic structure, or a structure with some weighting function, for the purpose of spurious suppression and size reduction. Periodic structures provide stop bands due to the well known Bragg effect. However, as compared to filters (where periodicity is sacrificed), periodic structures have intrinsic limitations such as moderate stopband bandwidth and the presence of ripple in the pass bands. Several works have been published (e.g. [51]), where, by sacrificing periodicity (through tapering and by continuously varying the unit cell dimensions), ripple is minimized, and the stopband bandwidth is enhanced.

In the present work, the intention is to achieve harmonic suppression and simultaneously reduce the size of the coupler by means of the slow wave effect related to the presence of inductances and capacitances, which effectively reduce the phase velocity of the constitutive artificial lines. Since we do not need, strictly speaking, a stop band filter, but a structure integrated within the coupler able to suppress the harmonic bands, the possible effects of ripple are not relevant in this case. For this main reason, tapering (or weighting) is not necessary in our structure. On the other hand, harmonic suppression of (at least) the first five bands is achieved, which is considered to be enough from a practical viewpoint. For all these reasons, the consideration of a purely periodic reactively-loaded artificial line makes sense in this work. Moreover, the structure must behave as a transmission line with an effective phase velocity and characteristic impedance, and its design on the basis of Floquet analysis, as it is done in the paper (mainly through equations 1, 2 and 8), is simple and effective. All these important considerations are not so simple by weighting.

Table 1 Comparison with previously reported miniaturized Rat-Race couplers

Ref.	Relative Size (%)	Harmonic Suppression	Harmonic Suppression Level (dB) *	Frequency of operation (GHz)	Matching bandwidth (%) ($S_{11} < -15$ dB)	Power splitting bandwidth (%) Σ/Δ (± 0.25 dB)	Phase balance bandwidth (%) Σ/Δ (± 5º)
[9]	32-46	NO	---	1.8	44.4	-/-	-/-
[29]	31	1st, 2nd, 3rd	30 / 40 / 18	0.5	58.7	23/23	17.6/17
[40]	15	1st	40	1	50	11/11	10.6/9.4
[41]	8	1st	40	1.44	24.3	12.5/12	-/10
[42]	3.9	NO	---	0.9	16.6	10/11	9/8.7
[43]	15	1st, 2nd , 3rd, 4th, 5th ,6th	12 / 38 / 32 / 28 /18 /10	1	42	20/21	-/15.5
[44]	27	NO	---	1	10	7/10	25/18
[45]	21.5	1st, 2nd	22 / 30	2.45	18.3	-/-	22/24.4
[46]	15	NO	---	2	15	-/-	-/-
[47]	17.8	1st, 2nd, 3rd, 4th	20 / 35 /45 / 30	1	24.3	20/20	10/13
[48]	5	NO	---	0.9	31.5	-/-	17/14
This work	18	1st, 2nd , 3rd, 4th, 5th	17 / 36 / 36 / 43 / 35	0.825	46	20/23	17/15

** The worst rejection level from output ports has been chosen.*

Table 2 Miniaturization methods used by the contributions reviewed in Table 1

Ref.	Miniaturization Method
[9]	Artificial transmission lines
[29]	Shunt open stubs
[40]	Capacitor loading
[41]	Slow-wave effect
[42]	Shunt-stub-based artificial transmission lines
[43]	Slow-wave resonant structures
[44]	Low impedance and fractal-shaped resonant cells
[45]	Periodic stepped-impedance
[46]	T-shaped PBG cells
[47]	Capacitive-inductive loading
[48]	Asymmetrical T-structures
This work	Slow-wave TLs with capacitive-inductive Loading

5. Conclusions

A compact rat-race coupler with harmonic suppression capability, based on slow-wave transmission lines with inductive and capacitive loading, has been reported. As compared to the ordinary coupler, the size has been 82% reduced, and the first five harmonic bands have been suppressed with more than 17 dB rejection. In certain applications, combining the coupler functionality with low-pass filtering is needed. Thus, space is saved if both functionalities are achieved with a single device, as demonstrated in this work. Moreover, the impact on miniaturization is further enhanced by means of the proposed slow-wave transmission lines. This combination of size and harmonic suppression is competitive. Note that a figure of merit in devices with harmonic/spurious suppression is the number of suppressed spurious bands and the rejection level. With the reported coupler, potential interfering signals at the output ports of the coupler (e.g., UWB signals) are avoided. Finally, the response of the coupler in the region of interest has been kept unaltered.

6. Acknowledgements

This work was supported by MINECO-Spain under Projects TEC2016-75650-R and TEC2017-84724-P, by Generalitat de Catalunya under project 2017SGR-1159, by ICREA (who awarded Ferran Martín), by the Spanish Junta de Andalucía under project P12-TIC-1435, and by FEDER funds.

7. References

[1] K. Wu, “Slow wave structures,” in *Encyclopedia of Electrical and Electronics Engineering*, J. G. Webster, Ed. New York: Wiley, 1999, vol. 19, pp. 366–381.

[2] F. Martín, *Artificial Transmission Lines for RF and Microwave Applications*, John Wiley, Hoboken (NJ), 2015.

[3] S. Seki, and H. Hasegawa, “Cross-tie slow-wave coplanar waveguide on semi-insulating GaAs substrates”, *Electron. Lett.*, vol. 17, pp. 940-941, Dec. 1981.

[4] T. Hirota, A. Minakawa, M. Muraguchi, “Reduced-size branch-line and rat-race hybrids for uniplanar MMIC's”,

IEEE Trans. Microw. Theory Techn., vol. 38, pp. 270-275, Mar. 1990.
[5] A. Görür, "A novel coplanar slow-wave structure," *IEEE Microw. Guided Wave Lett*., vol. 4, pp. 86–88, Mar. 1994.
[6] A. Görür, C. Karpuz and M. Alkan, "Characteristics of periodically loaded CPW structures", *IEEE Microw. Guided Wave Lett*., vol. 8, pp. 278-280, Aug. 1998.
[7] R. B. Singh and T. M. Weller "Miniaturized 20 GHz CPW quadrature coupler using capacitive loading", *Microw. Opt. Technol. Lett*., vol. 30, pp. 3-5, Jul. 2001.
[8] M. C. Scardelletti, G. E. Ponchak, and T. M. Weller, "Miniaturized Wilkinson power dividers utilizing capacitive loading", *IEEE Microw. Wirel. Compon. Lett*., vol. 12, pp. 6-8, Jan. 2002.
[9] K. W. Eccleston and S.H.M. Ong, "Compact planar microstripline branch-line and rat-race couplers", *IEEE Trans. Microw. Theory Tech*., vol. 51, pp. 2119-2125, Oct. 2003.
[10] J. García-García J. Bonache and F. Martín, "Application of electromagnetic bandgaps (EBGs) to the design of ultra wide band pass filters (UWBPFs) with good out-of-band performance", *IEEE Trans. Microw. Theory Tech*., vol. 54, pp. 4136-4140, Dec. 2006.
[11] C-I. Shie, J-C. Cheng, S-C. Chou, and Y-C. Chiang, "Transdirectional coupled-line couplers implemented by periodical shunt capacitors", *IEEE Trans. Microw. Theory Tech*., vol. 57, pp. 2981-2988, Dec. 2009.
[12] H. Cui, J. Wang and J.-L. Li, "Compact microstrip branch-line coupler with wideband harmonic suppression", *ACES Journal*, vol. 27, pp. 766-771, Sep. 2012.
[13] M. Orellana, J. Selga, M. Sans, A. Rodríguez, V. Boria, F. Martín, "Synthesis of slow-wave structures based on capacitive-loaded lines through Aggressive Space Mapping (ASM)", *Int. J. RF Microw. Comp. Aided Eng.*, vol. 25, pp. 629-638, Sep. 2015.
[14] J. Selga, P. Vélez, M. Orellana, A. Rodríguez, V. Boria, F. Martín, "Size reduction and spurious suppression in microstrip coupled line bandpass filters by means of capacitive electromagnetic bandgaps", *IEEE MTT-S Int. Microw. Symp*. (IMS'16), San Francisco, CA, 22-27 May 2016.
[15] M. Orellana, J. Selga, P. Vélez, A. Rodríguez, V. Boria, F. Martín, "Design of capacitively-loaded coupled line bandpass filters with compact size and spurious suppression", *IEEE Trans. Microw. Theory. Techn.*, vol. 65, pp. 1235-1248, Jan. 2017.
[16] L. Zhu, "Guided-wave characteristics of periodic microstrip lines with inductive loading: slow-wave and bandstop behaviors", *Microw. Opt. Techn. Lett*., vol. 41, pp. 77-79, Mar. 2004.
[17] S. Lee and Y. Lee, "Generalized miniaturization method for coupled-line bandpass filters by reactive loading", *IEEE Trans. Microw. Theory Techn.*, vol. 58, no.9, pp. 2383-2391, Sep. 2010.
[18] P. Vélez, J. Selga, J. Bonache and F. Martín, "Slow-wave inductively-loaded electromagnetic bandgap (EBG) coplanar waveguide (CPW) transmission lines and application to compact power dividers", *Europ. Microw. Conf.*, London (UK), 3-7 Oct. 2016.
[19] J. Selga, P. Vélez, J. Bonache, and F. Martín, "EBG-based transmission lines with slow-wave characteristics and application to miniaturization of microwave components", *Appl. Phys. A*, vol. 123, p. 44, Dec. 2016.
[20] S-G. Mao, and M-Y. Chen, "A novel periodic electromagnetic bandgap structure for finite-width conductor-backed coplanar waveguides", *IEEE Microw. Wireless Compon. Lett*., vol. 11, pp. 261-263, Jun. 2001.
[21] J. Sor, Y. Qian, and T. Itoh, "Miniature low-loss CPW periodic structures for filter applications", *IEEE Trans. Microw. Theory Techn*., vol. 49, pp. 2336-2341, Dec. 2001.
[22] H. M. Liu, S. J. Fang, Z. B. Wang, and Y. Zhou, "Miniaturization of trans-directional coupled line couplers using series inductors", *Prog. Electromagn. Research C*, vol. 46, pp. 171-177, Jan. 2014.
[23] J. Selga, P. Vélez, J. Coromina, A. Fernández-Prieto, J. Bonache, and F. Martín, "Harmonic suppression in branch-line couplers based on slow-wave transmission lines with simultaneous inductive and capacitive loading", *Microw. Opt. Tecnol. Lett*., submitted.
[24] M-L. Chuang, "Miniaturized ring coupler of arbitrary reduced size", *IEEE Microw. Wirel. Compon. Lett*., vol. 15, pp. 16-18, Jan. 2005.
[25] S-S. Liao, P-T. Sun, N.-C. Chin, and J-T. Peng, "A Novel Compact-Size Branch-Line Coupler", *IEEE Microw. Wirel. Compon. Lett*., vol. 15, pp. 588-590, Sep. 2005.
[26] J. Gu, and X. Sun, "Miniaturization and harmonic suppression of branch-line and rat-race hybrid coupler using compensated spiral compact microstrip resonant cell", *IEEE MTT-S Int. Microw. Symp*. (IMS'05), Los Angeles, CA, Jun. 2005.
[27] S.-S. Liao, and J.-T. Peng, "Compact planar microstrip branch-line couplers using the quasi-lumped elements approach with nonsymmetrical and symmetrical T-shaped structure", *IEEE Trans. Microw. Theory Techn*., vol. 54, pp. 3508-3514, Sep. 2006.
[28] J. Wang, B.-Z. Wang, Y.-X. Guo, L. C. Ong, and S. Xiao," A compact slow-wave microstrip branch-line coupler with high performance", *IEEE Microw. Wirel. Compon. Lett.*, vol. 17, pp. 501-503, Jul. 2007.
[29] P. Mondal A. Chakrabarty, "Design of miniaturised branch-line and rat-race hybrid couplers with harmonics suppression", *IET Microw. Antennas Propag*., vol. 3, pp. 109–116, Feb. 2009.
[30] V. K. Velidi, B. Patel, S. Sanyal, "Harmonic suppressed compact wideband branch-line coupler using unequal length open-stub units", *Int. J. RF Microw. Comput.-Aid. Eng.*, vol. 21, pp. 115-119, Jan. 2011.
[31] J. Selga, J. Coromina, P. Vélez, J. Bonache and F. Martín, "Application of electromagnetic bandgaps based on capacitively-loaded lines to the reduction of size and suppression of harmonic bands in microwave devices", *IEEE MTT-S International Conference on Numerical Electromagnetic and multiphysics Modeling and Optimization for RF, Microwave and Terahertz Applications* (NEMO), May, 17-19, 2017, Sevilla, Spain.
[32] J. Coromina, J. Selga, P. Vélez, J. Bonache, F. Martín, "Size reduction and harmonic suppression in branch line couplers implemented by means of capacitively-loaded slow-wave transmission lines", *Microw. Opt. Technol. Lett.*, vol. 59, pp. 2822–2830, 2017.
[33] C.W. Wang, T.G. Ma, and C.F. Yang, "Miniaturized branch-line coupler with harmonic suppression for RFID applications using artificial transmission lines," *IEEE Int. Microw. Symp. Digest*, Honolulu, HI, pp. 29–32, 2007.
[34] P. Kurgan, J. Filipcewicz, and M. Kitlinski, "Design considerations for compact microstrip resonant cells

dedicated to efficient branch-line miniaturization," *Microw. Opt. Technol. Lett*., vol. 54, pp. 1949–1954, Aug. 2012.
[35] P. Kurgan, J. Filipcewicz, and M. Kitlinski, "Development of a compact microstrip resonant cell aimed at efficient microwave component size reduction," *IET Microw., Ant. Propag*., vol. 6, no. 12, pp. 1291–1298, 2012.
[36] S. Koziel and P. Kurgan, "Low-cost optimization of compact branch-line couplers and its application to miniaturized Butler matrix design," *44th European Microwave Conference*, 6-9 Oct. 2014, Rome (Italy), pp. 227-230.
[37] K.-S. Choi, K.-C. Yoon, J.-Y. Lee, C.-K. Lee , S.-C. Kim , K.-B. Kim and J.-C. Lee, "Compact branch-line coupler with harmonics suppression using meander T-shaped line," *Microw. Opt. Technol. Lett*., vol. 56, pp. 1382–1384, Jun. 2014.
[38] S. Koziel and P. Kurgan, "Rapid design of miniaturized branch-line couplers through concurrent cell optimisation and surrogate-assisted fine-tuning," *IET Microw., Ant. Propag*., vol. 9, no. 9, pp. 957–963, 2015.
[39] G. Lian, Z. Wang, Z. He, Z. Zhong, L. Sun, and M. Yu, "A new miniaturized microstrip branch-line coupler with good harmonic suppression," *Progress In Electromagnetics Research Letters*, vol. 67, pp. 61-66, 2017.
[40] W.Shao, J. He, and B.-Z. Wang "Compact rat-race ring coupler with capacitor loading", *Microw. Opt. Technol. Lett*., vol. 52, no. 1, pp. 7-9, Jan. 2010.
[41] J. Wang, B.-Z. Wang, Y.-X. Guo, L.C. Ong and S. Xiao, "Compact slow-wave microstrip rat-race ring coupler", *Electronic letters,* vol. 43, no. 2, pp. 111-113, Jan. 2007.
[42] C. H. Tseng and H. J. Chen, "Compact rat-race coupler using shunt-stub-based artificial transmission lines," *IEEE Microw. Wirel. Compon. Lett*, vol. 18, no. 11, pp. 734-736, Nov. 2008.
[43] P. Kurgan and A. Bekasiewicz, "A robust design of a numerically demanding compact rat-race coupler", *Microw. Opt. Technol. Lett*., vol. 56, no. 5, pp. 1259-1263, May. 2014.
[44] P. Kurgan and M. Kitlinski, "Doubly miniaturized rat-race hybrid coupler", *Microw. Opt. Technol. Lett*., vol. 53, no. 6, pp. 1242-1244, Jun. 2011.
[45] J. T. Kuo, J. S. Wu and Y. C. Chiou, "Miniaturized rat race coupler with suppression of spurious passband," *IEEE Microw. Wirel. Compon. Lett*, vol. 17, no. 1, pp. 46-48, Jan. 2007.
[46] S. Opozda, P. Kurgan, and M. Kitlinski, "a compact seven-section rat-race hybrid coupler incorporating PBG cells", *Microw. Opt. Technol. Lett*., vol. 51, no. 12, pp. 2913-2913, Dec. 2009.
[47] S. Koziel, P. Kurgan, and B. Pankiewicz, "Cost-efficient design methodology for compact rat-race couplers," *Int J. RF Microw. Comp. Aid. Eng*, vol. 25, no. 3 pp. 236–242, Mar. 2015.
[48] C. H. Tseng and C. L. Chang, "A rigorous design methodology for compact planar branch-line and rat-race couplers with asymmetrical T-structures," *IEEE Trans. Microw. Theory Techn*., vol. 60, no. 7, pp. 2085-2092, Jul. 2012.
[49] J. Selga, P. Vélez, J. Bonache, F. Martín, "High miniaturization potential of slow-wave transmission lines based on simultaneous inductor and capacitor loading", *Proc. Europ. Microw. Conf.*, Nurember, Germany, October 2017.
[50] D. M. Pozar, *Microwave Engineering*, 4th Ed., John Wiley, Hoboken, NJ, 2012.
[51] M. A. G. Laso, T. Lopetegi, M. J. Erro, D. Benito, M. J. Garde and Mario Sorolla, "Novel wideband photonic bandgap microstrip structures", *Microw. Opt. Techn. Lett*., vol. 24, pp. 357-360, Mar. 2000.