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Narrowband bandpass filter exhibiting harmonic suppression

J. Fraresso and C.E. Saavedra

A novel bandpass filter is presented using ring resonators employing corrugated couplers in order to provide suppression of the second harmonic. The filter exhibits a 2.0% bandwidth at a centre frequency of 2.604 GHz and provides a 39 dB suppression of the second harmonic. The constituent resonator is described and an analogous bandpass filter without corrugations is presented for comparison.

Introduction: Ring resonators have found application in many devices including oscillators [1], filters [2], and tuned amplifiers [1] among others. The resonant frequencies of a ring resonator are all those frequencies for which the circumference of the ring represents an integral number of wavelengths. When quarter-wave couplers with a slow wave structure are used to couple energy into and out of the ring, the second harmonic is suppressed significantly [3].

If a perturbation is added to the ring, in the form of a stub, for example, dual modes will be excited because of the asymmetry introduced into the ring [4]. These dual modes can be exploited to design narrowband bandpass filters by aligning the modes so that their response coincides as closely as possible.

In this Letter we present a modification to the square resonators employing corrugated quarter-wave couplers on all sides of the ring described in [3] by adding a square perturbation in the inner corner of the resonator. The resonator is used as a constituent to construct a bandpass filter comprising two resonators coupled together with a three-line corrugated coupling structure.

Ring resonator design: The basic ring resonators of Fig. 1 were designed for a centre-frequency of approximately 2.6 GHz. The microstrip resonator circuits in this work were fabricated on a Rogers 4003 substrate with a relative dielectric constant of 3.4 and a thickness of 0.50 mm. The lengths of the quarter-wave couplers were chosen to be 15.2. mm ($\lambda/4$ at 3 GHz). The additional length added to the ring circumference by the mitred bends at the corners and the effect of the perturbation brought the resonant frequency down to 2.6 GHz.

In microstrip couplers without corrugations the odd model has a lower phase velocity than the even mode [5]. The corrugations employed on the coupler are used to equalise these phase velocities in order to improve the coupler directivity and, more importantly, in this application, to introduce a zero in the frequency response of the coupled port at the second harmonic. The couplers used have an average width of 1.17 mm, separation of 0.30 mm, a corrugation period of 0.90 mm, and a corrugation depth of 0.60 mm. The perturbation used was a 1.3 × 1.3 mm square located in the corner nearest the resonator input. The purpose of the coupled lines on the left- and right-hand side of the rings in Fig. 1 is to balance the characteristic impedance of the ring and to introduce symmetry into the structure [6].

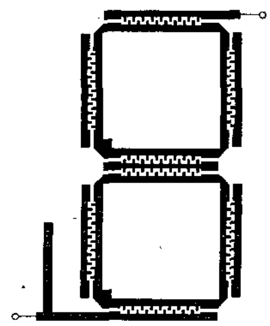

Fig. 1 *Narrow-band bandpas filter layout*

Narrowband bandpass filter: As shown in Fig. 1, the bandpass filter consists of two identical resonators connected together with a corrugated three-line coupler. The three-line coupler interconnecting the resonators was employed to avoid the mode splitting that occurs when using a two-line coupler to join the resonators. A transmission-line tuning stub was used at the filter input to optimise the return loss of the filter. The bandpass filter structure was simulated using a planar electromagnetic simulator and then measured using a vector network analyser using a thru-reflect-line (TRL) calibration. The simulated and experimental results are shown in Fig. 2. The experimental results of the bandpass filter reveal a centre frequency of 2.604 GHz, an insertion loss of 6.75 dB, and a percent bandwidth of 2.0%. Of significant importance is the 39 dB rejection of the second harmonic at 5.2 GHz with respect to the fundamental frequency.

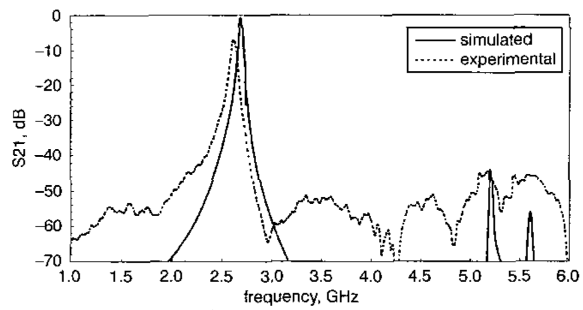

Fig. 2 *Filter response: simulated (solid) and experimental (dashed)*

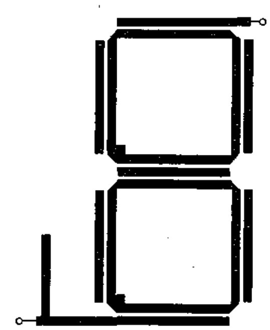

Fig. 3 *Non-corrugated bandpass filter layout*

For comparison purposes a bandpass filter was constructed in the same configuration using standard straight edge couplers. The filter and tuning stub are shown in Fig. 3 and the simulated and experimental results are shown in Fig. 4. The results indicate a centre frequency of 2.76 GHz, an insertion loss of 6.0 dB, a fractional bandwidth of 2.2%. The second harmonic in this filter experiences a rejection of only 2.5 dB with respect to the fundamental.

The advantage of the filter utilising couplers with a slow wave structure is readily discernable since it provides 37.5 dB more harmonic suppression than the filter with standard couplers while exhibiting a narrower bandwidth at the expense of a marginally larger insertion loss. It is valuable to note that the insertion loss can be improved by using a tighter coupling in and between the resonators but this would adversely impact the roll-off of the filter.

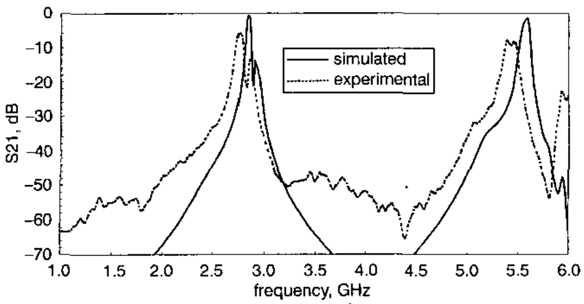

Fig. 4 *Filter response: simulated (solid) and experimental (dashed)*

Conclusion: A narrowband bandpass filter has been demonstrated with 39 dB second-harmonic suppression. The filter comprises two ring resonators using quarter-wave couplers with a slow-wave structure to couple energy into and out of the ring.

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Robust non-orthogonal space-time block codes over highly correlated channels: a generalisation

F.-C. Zheng and A.G. Burr

Little has so far been reported on the robustness of non-orthogonal space-time block codes (NO-STBCs) over highly correlated channels (HCC). Some of the existing NO-STBCs are indeed weak in robustness against HCC. With a view to overcoming such a limitation, a generalisation of the existing robust NO-STBCs based on a 'matrix Alamouti (MA)' structure is presented.

Introduction: Little has so far been reported on the robustness of non-orthogonal space-time block codes (NO-STBCs) over highly correlated channels (HCC), which do exist in practice. Some of these codes, e.g. the ABBA code in [1, 2], are weak in robustness: their channel matrices will become ill-conditioned over highly correlated channels (HCC), potentially leading to the collapse of all decoding algorithms. With a view to overcoming such a limitation, this Letter presents a generalisation of the robust NO-STBCs [3] based on a 'matrix Alamouti' structure.

Robustness of NO-STBC: Consider a system with four transmit (Tx) and one receive (Rx) antennas. For a group (input) of four complex symbols, s_1, s_2, s_3, and s_4, the output of the NO-STBC coder is a 4×4 matrix $\mathbf{C} = [c_{ij}]$, where c_{ij} is either $\pm s_k$ or $\pm s_k^*$ (conjugate of s_k), and is transmitted by Tx j at time i. By letting the channel gain from Tx j to the Rx be h_j (which remains constant over the four-symbol period), the received signal at time i is $r_i = \prod_{j=1}^{4} h_j c_{ij} + n_i$, where n_i is the complex Gaussian noise with zero mean and a variance of σ_n^2 (therefore $0.5\sigma_n^2$ per dimension). Also, $|h_j|$ is subject to Rayleigh fading but is normalised, i.e. $\mathrm{Re}[h_j]$, $\mathrm{Im}[h_j] \sim N(0, 0.5)$.

Let

$$\mathbf{g}_{ij} = \begin{bmatrix} s_i & s_j \\ -s_j^* & s_i^* \end{bmatrix}$$

(i.e. $\mathbf{g}_{ij}$ the standard Alamouti matrix involving symbols s_i and s_j). The ABBA code [1] can then be constructed as:

$$\mathbf{C}_{ABBA} = \begin{bmatrix} \mathbf{g}_{12} & \mathbf{g}_{34} \\ \mathbf{g}_{34} & \mathbf{g}_{12} \end{bmatrix}$$

where $[\cdot]^*$ means 'conjugate'. This leads to the following compact form for the received signal:

$$\mathbf{r} = \mathbf{Hs} + \mathbf{n} \tag{1}$$

where $\mathbf{r} = [r_1, r_2^*, r_3, r_4^*]^T$, $\mathbf{s} = [s_1, s_2, s_3, s_4]^T$, $\mathbf{n} = [n_1, n_2^*, n_3, n_4^*]^T$ and the corresponding channel matrix $\mathbf{H}$ is

$$\mathbf{H}_{ABBA} = \begin{bmatrix} \mathbf{h}_{12} & \mathbf{h}_{34} \\ \mathbf{h}_{34} & \mathbf{h}_{12} \end{bmatrix}$$

where

$$\mathbf{h}_{ij} = \begin{bmatrix} h_i & h_j \\ h_j^* & -h_i^* \end{bmatrix}$$

One major limitation of the above ABBA code is its lack of the desirable robustness against HCC. The worst case for HCC comes when $h_1 = h_2 = h_3 = h_4 = h$. This will result in the following *singular* channel matrix:

$$\mathbf{H}_{ABBA} = \begin{bmatrix} h & h & h & h \\ h^* & -h^* & h^* & -h^* \\ h & h & h & h \\ h^* & -h^* & h^* & -h^* \end{bmatrix} \tag{2}$$

which leads to the collapse of all detection/decoding algorithms (e.g. maximum likelihood, zero-forcing and interference cancellation). In fact, as long as there is a high correlation h_i's, between $\mathbf{H}_{ABBA}$ will become ill-conditioned, causing the detection results to be highly unreliable [1].

Generalisation of robust NO-STBC: The question now is how to improve the robustness of the ABBA-like codes. Clearly, $\det(\mathbf{H}_{ABBA}) = 0$ in (1) is caused by the special ABBA structure of the channel matrix $\mathbf{H}$ (here $\det(\mathbf{A})$ denotes the determinant of $\mathbf{A}$). To improve the robustness of the ABBA-like codes against HCC, we must have $\det(\mathbf{H}) \neq 0$, even when $h_j = h$, $j = 1, 2, 3, 4$. A natural way of achieving this is to alter the structure of $\mathbf{H}$ (the entries of $\mathbf{r}$ also need to be changed accordingly). To this end, let us consider all the possible structures of $\mathbf{H}$ under $h_j = h$:

$$\mathbf{H} = \mathbf{F} \otimes \mathbf{h} \tag{3}$$

where

$$\mathbf{h} = \begin{bmatrix} h & h \\ h^* & -h^* \end{bmatrix}$$