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Filtering Two-element Waveguide Antenna Array Based on Solely Resonators

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Abstract

This paper presents a design approach of a filtering antenna arrays based on the coupling matrix theory. The approach generates filtering functionality using the resonating array radiating elements and the resonator based feed network regardless to the physical structure. To implement the approach, a novel topology for a two-element array is presented, here three rectangular waveguide cavity resonators have been employed to form the filtering array. The array has a fractional bandwidth of 10% at the centre frequency 10 GHz with a reflection coefficient magnitude within the passband of 20 dB. The realised gain over the passband is 9.8 ± 0.4 dBi. The array has been fabricated and the measurements are in very good agreement with the simulations, validating the approach.

Keywords: filtering antenna array, waveguide resonators, antenna array, coupling matrix.

1. Introduction

Filtering antenna arrays combine the filtering functionality of front-end Bandpass Filters (BPFs) and the radiation properties of the antenna arrays. Such integration not only miniaturises the size of the front-end of a communication system, but also improves the performance by removing the losses due to the integration of usually separate components [1-4]. Various synthesis approaches have been presented in the literature, implemented using different radiating structures such as printed inverted-L, L-shaped, and microstrip patch [1, 5, 6].

Enhancing the bandwidth of filtering antenna arrays has been a focus more recently due to the constant requirements for an increase in the data rate capability for the modern wireless systems. For example, in [7] a waveguide aperture is mounted on a ground plane so as to excite the surface waves and enlarge the bandwidth. A slot antenna and a filter were integrated vertically and presented in [8] in order to reduce the total size and improve the efficiency of the system. Additional bandwidth enhancement techniques of filtering antenna arrays have been reported in [9]. Filtering the array feed network and making the cascaded radiators act as the last coupled resonators of the BPF is another technique which has been utilised in the design of filtering array [10]. Also, the filtering functionality feature has been introduced to the mono-pulse antenna array based on the substrate integrated waveguide structure [11].

Horn antennas, which are high gain and very efficient antennas, are also of interest to integrate with BPFs. A small cross-meandered slot resonator etched on a plate was inserted into the throat of a horn antenna in order to not only achieve filtering functionality, but also to achieve polarisation transformation [12]. Similarly, a filtering chiral particle module was designed and placed between two orthogonally connected waveguides to rotate the polarisation [13]. The same module was utilized at the waveguide section of the horn antenna in order to rotate the polarisation,

and also to narrow the matching bandwidth resulting filtering horn antenna [13]. The design of a notched filter together with horn antenna was investigated in [14] by placing two Split Ring Resonators (SRRs) where the flare out of the horn starts. The spacing between the SRRs were manipulated to introduce the matching bandwidth tunability. Recently, the utilization of metamaterials in the integration of filters with antennas has been appeared in the literature. A notched filter integrated with horn antenna was investigated by utilizing various metamaterial resonators [15]. A metasurface based linear-to-circular polarised transformer was presented in [16], and was used in a pyramidal horn antenna to create circularly polarised radiation.

In this work a design approach of filtering antenna arrays has been investigated which is based on the coupling matrix [17]. This introduces the filtering functionality to the array feeding network, together with the radiating elements and includes a specification of bandwidth. Previously, we have utilized this approach in the design of a 4×4 filtering planar antenna array [4]. In this paper, for the first time, we propose a novel topology for the design of two-element filtering array based solely on resonators. The topology presented here allows the array to use resonators not only for the feed network but also as the radiators, forming a compact filtering two-element array.

2. Topology and Design Procedure

Fig. 1 (a) shows the proposed 2nd order topology of the two-element array. It is called 2nd order due to it using only two resonators in each of the radiating output paths, it is a term often used in filter design. The array consists of single input resonator coupled to two *resonator-radiators* which act as radiators in addition to their filtering roles. The input resonator and one *resonator-radiator* are shared in each of the radiating outputs. Thus, the network forms a bandlimited power splitter

with a two-pole filter in each of the channels. Fig. 1 (b) shows the physical structure of the array formed of rectangular waveguide resonators. For clarity, the surrounding conductor is set to be transparent and the air inside the structure as can be seen.

Fig. 1 (a) Topology of the Filtering two-element antenna array, (b) Physical configuration of the topology based on the rectangular waveguide cavity resonators.

It is important to mention that the coupling matrix approach can be applied to any kind of resonator regardless to its physical structure and operating frequency band [17]. Although the approach is based on the narrow bandwidth approximation [17], it is still applicable for larger bandwidth applications if the employed resonators can provide the required inter-resonator coupling coefficients and quality factors. This has been discussed in our previous work [18].

In this work, the coupling matrix approach has been utilised to design a two-element filtering antenna array using rectangular waveguide technology. The electrical specifications are a *FBW* of 10% at a centre frequency (f_0) of 10 GHz with a reflection coefficient (S_{11}) within the passband of 20 dB. These are chosen arbitrary in order to validate the approach. It is important to mention that these electrical specifications are used to generate the coupling matrix which is then used to extract

of the physical dimensions of the filtering array. The useful parameters are the external quality factor (q_{e1}), radiation quality factor (q_{rn}), and coupling coefficients (m_{ij}) between the resonators; these are shown in Fig. 1 (a). In the following sub-section , details regarding the calculations of q_{e1} , q_{rn} , and m_{ij} parameters are presented, and their extractions from the equivalent physical structures are discussed.

2.1 External Quality Factor (q_{e1}) Extraction

Following the coupling matrix formulation [17], the scaled external quality factor q_{e1} ($q_{e1} = Q_{e1} \times FBW$) value can be obtained from the Chebyshev filter response. Q_{e1} is non-scaled external quality factor which can be extracted from a simulation of the physical structure shown in Fig. 2 (a) using the following equation [17]:

$$Q_{e1} = \frac{f_0}{\Delta f_{3dB}} \quad (1)$$

Δf_{3dB} is the 3-dB fractional bandwidth of the transmission coefficient (S_{21}) which can be obtained from the response using the CST simulator [19] as illustrated in Fig. 2 (b). It should be mentioned that during the extraction of the dimensions, one side of the input resonator is coupled to the input port via an iris with a width dimension d_0 , as shown in Fig. 2 (a), while the other side is weakly coupled to the output port using a narrow aperture. A parametric study has been performed and presented in Fig. 2 (c). As expected, Q_{e1} value decreases with an increase of d_0 . In Fig. 2 (c) the resonator length (l_1) is adjusted to keep the resonating frequency at 10 GHz. Based on the chosen electrical specifications of the filtering array, the Q_{e1} value is equal to 6.648 using the g-element values of a two-port filter [17]. From curve fitting of Fig. 2 (c), the d_0 dimension, which provides such a Q_{e1} value, is equal to 6.62 mm.

(a)

(b)

(c)

Fig. 2 (a) Physical configuration of the input resonator for the coupling iris (d_0) dimension extraction. (b) The S_{21} response of the input resonator using the CST simulator. (c) The variations of the external quality factor (Q_{e1}) and resonator length l_1 versus d_0 at 10 GHz.

2.2 Radiation Quality Factor (Q_m) Extraction

It is important to note here that the quality factor Q_{e1} discussed above is exactly the same as in a conventional filter for the input resonator [20], however for the output resonators (*resonator- radiators* shown in Fig. 3 (a)) it is equivalent to the non-scaled radiation quality factor (Q_m). In order to maintain the impedance matching between the input port and radiation output ports, the Q_m must be equal to Q_{e1} . In this work, the Q_m is calculated using the one-port measurement technique [21] using:

$$Q_m = \frac{1}{|\Delta f_a|} \left[\frac{|S_{11}(f_a)|^2 (1+\beta)^2 - (1-\beta)^2}{1 - |S_{11}(f_a)|^2} \right]^{1/2} \quad (2)$$

Where f_a is some frequency points near the resonant centre frequency (f_0), and is located within the passband of the magnitude of S_{11} response of the *resonator- radiator* as shown in Fig. 3 (b). It is mentioned in [21] that the accuracy in the calculation of Q_m can be increased when multiple values of f_a are used and then averaging the Q_m value. Therefore, in this work, around 50 different values of f_a are used. $\Delta f_a = 1 - (f_0/f_a)^2$, and β is the coupling coefficient between the *resonator- radiators* and free space [21].

The desired Q_m value, i.e. $Q_m = Q_{e1} = 6.648$, can be obtained utilising the aperture dimension (l_a) of the *resonator-radiators* coupled to free space as labelled in Fig. 3 (a). As expected, the Q_m value decreases with an increase of l_a as presented in Fig. 3 (c). With any change of l_a , the length of the *resonator- radiator* (l_r) is adjusted in order to keep the resonating frequency at 10 GHz. For the required Q_m value (6.648) of the proposed filtering array, the l_a value is found to be equal to 17.22 mm as seen in Fig. 3 (c).

(a)

(b)

(c)

Fig. 3 (a) Physical configuration of the *resonator-radiator*. (b) The S_{11} response of the *resonator-radiator* using the CST simulator. (c) variation of the radiation quality factor (Q_m) versus various radiating aperture dimensions l_a at 10 GHz.

2.3 Coupling Coefficients (m_{ij}) Extraction

To determine the required scaled coupling coefficients m_{ij} ($m_{ij}=M_{ij}/FBW$) between the input resonator and *resonator-radiators*, the corresponding Chebyshev filter specification is used. A gradient-based optimisation algorithm [20] is utilised in order to find the 3×3 equivalent coupling matrix $[m]$ of the filtering array, the result is:

$$[m] = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{11} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} = \begin{bmatrix} 0 & 1.175 & 1.175 \\ 1.175 & 0 & 0 \\ 1.175 & 0 & 0 \end{bmatrix} \quad (3)$$

It is important to mention that the optimisation of the matrix is performed based on the chosen electrical specifications of the filtering array. In terms of physical structure, the non-scaled coupling coefficient ($M_{12} = M_{13}$) can be extracted from the structure in Fig. 4 (a) where the input resonator and *resonator-radiators* are coupled to each other via an iris with a width d_r as shown in Fig. 4 (a) using equation [17]:

$$M_{12} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \quad (4)$$

Here f_1 and f_2 are frequencies which can be extracted from the S_{21} response using the CST simulator as shown in Fig. 4 (b). The coupling iris width (d_r) controls M_{12} as shown in Fig. 4 (c). An increase of d_r increases M_{12} . The d_r dimension of the proposed filtering array, which is equivalent to $M_{12} = 0.1175$ value, is found to be 9.30 mm as seen in Fig. 4 (c).

Fig. 4 (a) The configuration for the M_{12} extraction. (b) The S_{21} response of the input resonator and resonator-radiators using the CST simulator. (c) the variation of M_{12} versus coupling width (d_r) at 10 GHz.

Before continuing it should be noted that the S_{11} of the filtering array can be calculated using the coupling matrix equation [17] as follows:

$$S_{11} = 1 - \frac{2}{q_{e1}} \cdot [A]_{11}^{-1} \quad (5)$$

Here $[A]$ is the sum of three matrices as given below:

$$[A] = [q] + p[U] - j[m] \quad (6)$$

For the specifications presented here this is,

$$[A] = \begin{bmatrix} \frac{1}{0.6648} & 0 & 0 \\ 0 & \frac{1}{0.6648} & 0 \\ 0 & 0 & \frac{1}{0.6648} \end{bmatrix} + p \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - j \begin{bmatrix} 0 & 1.175 & 1.175 \\ 1.175 & 0 & 0 \\ 1.175 & 0 & 0 \end{bmatrix} \quad (7)$$

Where $[q]$, $[U]$, $[m]$ are the quality factor matrix, the unit matrix, and coupling matrix respectively.

p ($p = j/FBW (\omega/\omega_0 - \omega_0/\omega)$) is complex frequency variable, ω is angular frequency, and ω_0 is angular centre frequency.

After inserting (7) into (5) with all the predetermined parameters, the S_{11} response of the filtering array can be calculated. It is compared and discussed with the simulation in the following section.

3. Antenna Design and Results

The physical configuration of the proposed array has been shown in Fig. 1 (b). Capacitive irises are utilised to couple the input resonator to the input port and the *resonator-radiators* in order to realise strong couplings. The *resonator-radiators* are coupled to free space via radiating apertures. They are spaced by a half free space operating wavelength ($0.5\lambda_0$). The initial values of the dimensions d_0 , l_a , d_r , which alter the Q_{e1} , Q_m , and M_{12} respectively, are extracted using the techniques presented in Section 2. The whole structure is put together with these initial sizes and optimized in the CST simulator. All the optimized dimensions obtained are given in Table 1. The S_{11} and realised gain obtained using the CST simulator, as well as the matrix calculation, are shown in Fig. 5. During the simulation, the material chosen for the filtering array was Aluminium Alloy (conductivity = 3.56×10^7 S/m). The simulated S_{11} is in a very good agreement with the desired

coupling matrix response. The total efficiency, as shown in Fig. 6, is more than 95 % over the passband.

Fig. 5 Simulated realised gain, and S_{11} responses compared with the coupling matrix.

Fig. 6 Simulated total efficiency of the two-element filtering array.

Table 1: Physical dimensions of the two-element filtering array shown in Fig. 1 (b).

Dimensions	Values in mm
a	22.86
b	10.16
c	2.0
t_r	9.0
d_0	6.62
d_r	9.30
l_0	10.0
l_1	24.51
l_r	18.0
l_a	17.22
round corners	1.6

4. Fabrication and Measurements

Fig. 7 shows the photograph of the proposed filtering antenna array which is made from Aluminium Alloy 6082. A Computer Numerical Control (CNC) milling machine has been used for the fabrication which has a tolerance of $\sim \pm 0.02$ mm. The array is made out of two pieces, splitting at the centre of the broad wall along the zero-current line of the resonators. This is to facilitate the fabrication process and minimise the insertion loss.

Fig. 7 Photograph of the fabricated two-element filtering antenna array.

The radiation characteristics have been measured in an anechoic chamber as shown in Fig. 8. The well-known comparison method has been used to measure the realised gain where an X-band horn antenna has been used as a reference antenna. It is seen in Fig. 9 that the measured realised gain and S_{11} are in very good agreement with the simulations. The maximum S_{11} is close to -20 dB from 9.5 GHz to 10.5 GHz. The realised gain is flat, changing from 9.5 to 10.2 dBi over the passband. The 3-dB gain-bandwidth is 27 % at $f_0=10$ GHz.

Fig. 8 Filtering antenna array under test in an anechoic chamber

It should be mentioned that the out-of-band attenuation level is not as large as the one we presented in [4]. This is due to employing fewer resonators to create each of the radiating path. Usually, the attenuation level could be improved by employing more resonators, and this has been addressed in our previous work [20]. Employing more resonators may not be an optimal solution due to the larger size. A better solution is to add transmission zeros around the start and stop bands frequencies. Such transmission zeros are a well know technique used in filter design. This could be achieved by introducing additional coupling between the input and resonators 2 and 3. To

implement this, the $N+2$ coupling matrix could be an interesting tool to be considered [22]. This is currently under the investigation.

Fig. 9 Measured realised gain and S_{11} responses compared with the Simulated

The radiation patterns have been measured at various frequency points within the passband. Very good patterns in terms of main beam scan and side lobe levels were noticed as shown in Fig. 10. Excellent agreement between the simulation and measurement is obtained. The asymmetry of the patterns in the H-plane is due to the asymmetric configuration of the prototype on that plane. The side lobe level is very low, especially in the E-plane (below -20 dB). This is due to small non-radiating area and inter-element space ($0.5\lambda_0$) in that plane. The cross-polarisation is below -15 dB in both of the planes. It is worth mentioning that the coupling matrix approach used in this paper can, in principle, address the mutual coupling effect between the radiating outputs. However, it is not considered here because it is too small, and close agreement between the simulated and calculated S_{11} is an indication of that.

(a)

(b)

(c)

Fig. 10 Simulated and Measured radiation patterns at (a) 9.5, (b) 10, and (c) 10.5 GHz.

Conclusion

A two-element filtering antenna array has been designed using a novel topology configuration. The coupling matrix approach was used in the design. For demonstration, rectangular waveguide resonators were utilized to demonstrate the topology and CNC milling was used for the fabrication. The array realised gain was very stable over the passband with a value of 9.8 dBi and ~ 0.4 dBi variation. The *FBW* was 10% at $S_{11} = -20$ dB. Measurements were in very good agreement with the simulation, indicating that the approach is good for the design of large bandwidth filtering antenna array.

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