Compact All-metal In-line Combline Coaxial Cavity Diplexer

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Abstract — This article describes the design of an all-metal combline coaxial cavity diplexer. The device is based on a Y-shaped star-resonant junction which allows to achieve a compact design by positioning the two channels in an in-line and side-by-side arrangement. The channels share the same geometry and are tuned to resonance using screws. The device was designed using the coupling matrix method. For verification, a combline cavity diplexer was manufactured and tested for E1 Galileo (1559–1591 GHz) and Iridium (1606–1638 GHz) applications with fractional bandwidth equaling 2% for both channels. The order and the return loss of each channel are 5 and 19.4 dB, respectively. The volume is 154.1 × 36 × 27.8 mm^3, corresponding to a normalized volume of 0.810 × 0.189 × 0.146 λ^3. The normalized volume per resonator is as low as 0.0047 λ^3, while isolation is better than 55 dB. The ratio between the unloaded quality factor and the normalized volume per resonator is as high as 19.8 × 10^4 λ^{-3}. The design is very easy to manufacture, since it is all-metal and has a simple geometry.

Keywords* — *cavity, combline resonators, diplexer, L band

1. Introduction

Microwave diplexers are essential components of RF systems, including cellular base stations and satellite payloads [1]. They are useful in transceiver systems, where the transmitter and receiver signals are close within the frequency spectrum, or when a system operates with two close frequency services. The combline coaxial cavity technology offers low losses and high selectivity and supports high-power signals (hundreds or even thousands of watts). However, this comes at the cost of the occupied volume, which is high, i.e. in the region of tenths of λ^3, compared to microstrip technology [2]–[4]. Therefore, several designs have been introduced to shrink the sizes of cavity filters, either by relying on dual mode operation [5], [6], multi-conductor coaxial cavity resonators [7]–[9] or dielectric resonators [10]–[12].

Combline resonators are an evergreen topic of interest within the microwave community. First papers about combline filters appeared in the 1960s and 1970s [13]–[15] and a comprehensive reference book, which still remains in use, was published in the early 1980s [16]. A deeper understanding of combline filters was obtained in the 1990s and 2000s [17]–[20], when the basics and the fundamentals of combline filters and diplexers were laid down. However, this did not stop research on combline resonators which continued in the following decades and is still conducted nowadays [21]–[23] – all in an effort to ensure better performance and devise tunable devices.

This paper presents a compact all-metal in-line combline coaxial cavity diplexer with enhanced performance. A resonating star junction feeds the two channels. A Y-shaped design is used for the junction, allowing the two channels to be positioned in an in-line arrangement. Since the two channels operate at nearby frequencies, their physical dimensions are the same, and the different resonating frequencies are obtained using tuning screws.

For verification purposes, a diplexer for the E1 Galileo (1559–1591 GHz) and the Iridium (1616–1626.5 GHz) frequency bands was manufactured and tested. The prototype is intended for the LaBarchettaMagica – a showcase, self-navigating vessel built under the VELA project [24]. The simple geometry and the lack of dielectric materials make this cost-effective design easy to manufacture.

2. Design Process

The diplexer model developed is shown in Fig. 1. It is made up of two filters that are joined by a Y-shaped resonating star

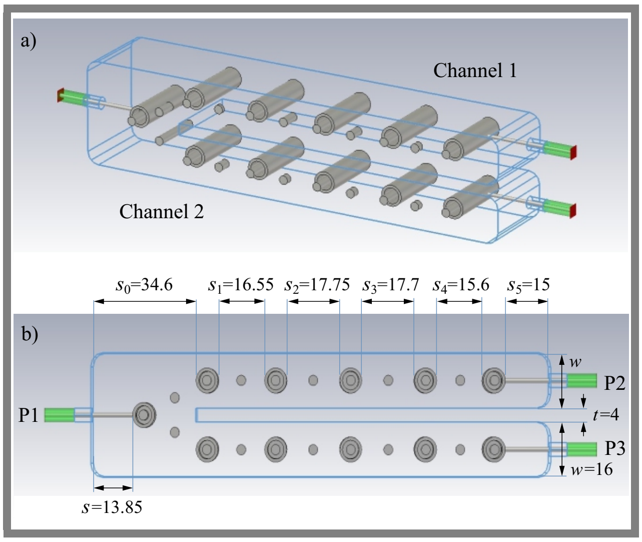

Fig. 1. Model of the diplexer: a) perspective and b) top views. The dimensions (in mm) are: the coaxial inner (outer) diameter is 5.5 and 7.3, the screw diameter is 3, the coaxial cable inner and outer diameters are 1.27 and 4.1, respectively. The heights of the tap points from the bottom of the cavity are 18.75 for P1, 6.75 for P2, and 6.90 for P3, respectively. The radius of the fillets is 4.

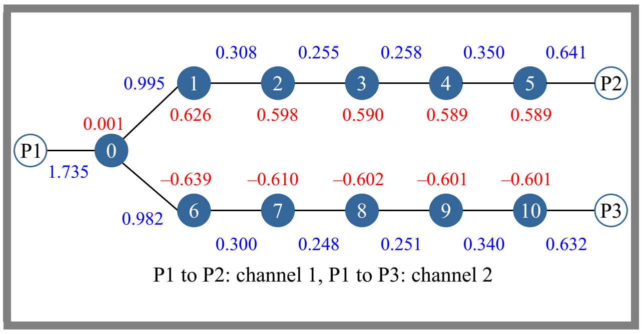

Fig. 2. Topology of the diplexer. The blue circles indicate the resonators, while white circles stand for ports. The numbers in red indicate normalized resonant frequencies $m_{i,i}$, while those in blue indicate normalized coupling coefficients $m_{i,j}$. The white numbers indicate the number of resonators.

junction [25]. The design of a single filter is the same as that described for the filters in [26]–[29]. Then, another filter with the same dimensions is created and aligned with the first one. The separation distance between the two channels is $t = 4$ mm. All coaxial resonators are equal, for ease of manufacture. Their height is $\frac{\lambda}{8}$, with λ being the wavelength at 1.575 GHz. Since the two bandwidths are close, each channel may be tuned to the desired bandwidth [28]. The coupling between adjacent resonators is predominantly of the magnetic type. The input and output couplings are obtained by tapping. To enable the resonators to be tuned to resonance, tuning screws are added above each resonator. To ensure a flexible tuning process, coupling screws are also added midway between the resonators.

The distance between the common resonator and the left-hand side wall is s, while the length of the cavity and its width are s_0 and $2w + t$, respectively (Fig. 1). The star junction is described by s_0 and s parameters, and their values are approximately equal to $2w + t$ and s_5, respectively.

The diplexer has been designed using the coupling matrix method [30]. In view of the above, a return loss (RL) of 19.4 dB is considered, while the passbands of the two channels are 1559–1591 GHz and 1606–1638 GHz, i.e. fractional bandwidth equals 2% for both channels. The number of resonators for each channel is $N = 5$. For the synthesis of the coupling matrix, we rely on the filter toolbox of the CST Studio Suite [31]. The corresponding topology of the diplexer is depicted in Fig. 2, together with the non-zero entries of the synthesized coupling matrix.

The denormalization of the coupling matrix is carried out as in [32], and the values of the resonant frequencies, coupling coefficients, and external quality factors are listed in Tab. 1. Although the desired values for the external quality factors of P2 and P3 are similar, the external quality factor for P1 is significantly lower.

Furthermore, note that the coupling coefficients $k_{0,1}$ and $k_{0,6}$ between the junction resonator and resonators 1 and 6, as shown in Fig. 2, are approximately three or four times greater than the coupling coefficients between the other resonators of the two channels.

Tab. 1. Resonant frequencies (Res. f.), coupling coefficients $k_{i,j}$, and external quality factors Q_E for the proposed design. Res. no. stands for resonator number, as indicated in Fig. 2.

Res. no.	Res. f. [MHz]	$k_{i,j}$		Q_E	
0	1597.98	$k_{0,1}$	0.0492	P1	6.72
1	1573.46	$k_{1,2}$	0.0153	P2	49.23
2	1574.58	$k_{2,3}$	0.0126	P3	50.70
3	1574.87	$k_{3,4}$	0.0128		
4	1574.91	$k_{4,5}$	0.0173		
5	1574.92	$k_{0,6}$	0.0485		
6	1623.43	$k_{6,7}$	0.0148		
7	1622.27	$k_{7,8}$	0.0123		
8	1621.97	$k_{8,9}$	0.0124		
9	1621.93	$k_{9,10}$	0.0168		
10	1621.92				

Note that no cross-coupling is implemented in the proposed diplexer. However, techniques are available to realize in-line cross-couplings [33], [34]. Finally, the dimensions of the coaxial resonators and channel cavities are obtained from the approaches referred to in [35], [36] and are reported in Fig. 1b.

3. Characterization

Figure 3 shows the manufactured diplexer. The cavity is split into two parts, known as the main body and the lid. The lid features a step to prevent radiation leakage and is attached to the main body with 36 M2 screws. The coaxial resonators are manufactured separately and fastened to the bottom of the cavity using screws. The material for the main body, the lid, and the resonators is 6082 aluminum alloy, and no plating is applied. Instead, M3 tuning and coupling screws are made of brass and are fastened to the lid. The input and output ports are realized with SMA connectors. They have a solder cup to connect the wires needed for tapping. The dimensions of the diplexer are 154.1 × 36 × 27.8 mm^3 without the walls, and 162.1 × 44 × 37.8 mm^3 with the walls included.

First, the external couplings are adjusted. In Fig. 4, the measured group delay is shown at the three ports – the resonators at the ports are tuned, while the others are short-circuited, as in [26], [29]. The link between the external quality factor Q_E and the group delay τ_d at the center frequency f_0 is:

$$Q_E = \frac{\pi f_0}{2} \tau_d \, , \tag{1}$$

where no losses are assumed.

The group delays obtained at the center frequencies for the three ports are: 3.1, 20.7, 20.8 ns. These values correspond to the following external quality factors achieved: 7.7, 51.2,

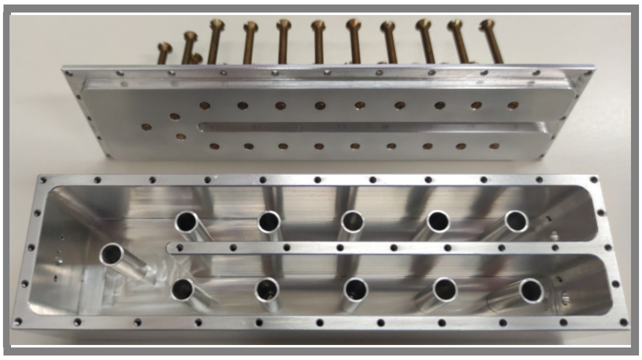

Fig. 3. Manufactured diplexer.

53.0. In Fig. 4, note the wider bandwidth of the group delay of P1, which comprises the bandwidths of both P2 and P3.

Next, the filter is tuned by adjusting the screw penetrations inside the cavity. In Fig. 5, the measured and synthesized magnitude of the scattering parameters is compared. Overall, a good agreement is achieved. In the manual tuning process, the bandwidth of channel 2 has been slightly decreased. However, the Iridium bandwidth is completely contained within the realized bandwidth of channel 2. RL satisfies the specifications requirements and equals at least 19.4 dB in the two bandwidths. A slight deviation for $|S_{21}|$ appears when the frequency is less than 1.559 GHz, due to the manual tuning and the non-ideal frequency characteristics of the coaxial resonators. Note that isolation (ISO) between the channels is as foreseen by the synthesized response, i.e. it is greater than 55 dB at the center frequencies of the channels.

Finally, the measured wideband response of the diplexer is depicted in Fig. 6. For both channels, spurious peaks occur at approximately three times the center frequency of each channel.

In Tab. 2, the performance of this diplexer is compared with other devices sharing the same technology (cavity resonators) described in the literature. To assess compactness, a figure of merit (FoM_1) is introduced. This is equal to the normalized volume per resonator and analogous to the one adopted in [5], [40]. The proposed diplexer is the only one, together with [9], with $\mathrm{FoM}_1 < 0.5 \cdot 10^{-2}\,\lambda^3$. The ISO achieved has one of the highest values, comparable with [5], [37]. Insertion loss (IL) is 1.65 dB for channel 1 and 1.70 dB for channel 2, and corresponds to an unloaded quality factor, averaged over the resonators, of $Q_u \approx 925$. IL is approximately 1 dB higher than that usually characterizing such a class of diplexers, but losses could be reduced either by design changes consisting in varying the shapes of the resonators and the lid, or by technological modifications consisting in plating the interior of the filter with a highly-conductive material.

An additional figure of merit FoM_2, equal to the ratio between Q_u and FoM_1, is introduced. Its value is $19.8 \cdot 10^4\,\lambda^{-3}$, and thus represents the highest value among those reported in Tab. 2. The weight of the prototype is 422 g and is comparable with the mass of analogous diplexers intended for satellite systems, such as the one described in [12], where a weight of 480 g is declared.

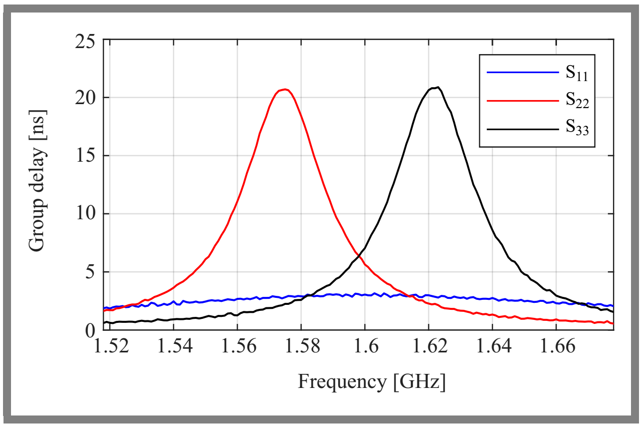

Fig. 4. Group delay measured at the three ports.

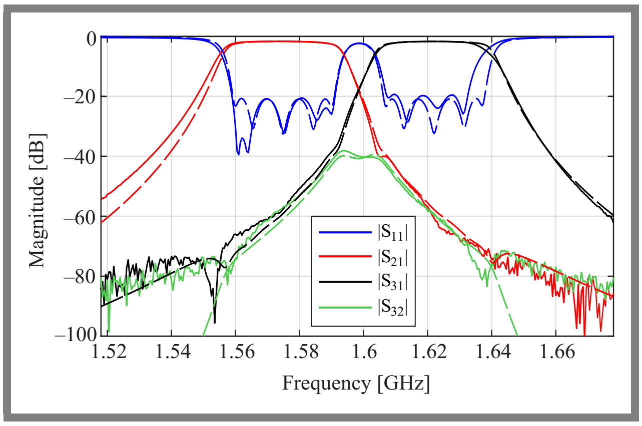

Fig. 5. Comparison between synthesized and measured responses: the former are plotted with dashed lines, the latter with solid ones.

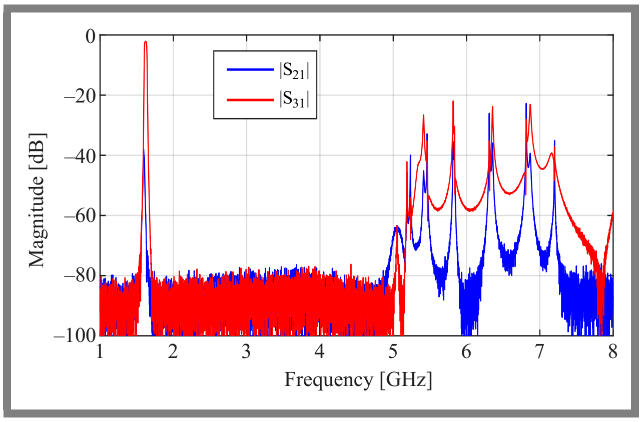

Fig. 6. Measured wideband response in the range 1–8 GHz.

4. Conclusions

The paper presents the design of a combline coaxial all-metal in-line diplexer, where the resonating star junction – a Y-shaped junction – is adopted. The new design is first outlined and then experimentally verified with a diplexer for E1 Galileo and Iridium applications (L band). Both channels have five resonators and are characterized by the same dimensions. The different resonant frequencies are obtained by adjusting screw penetrations.

Tab. 2. Performance comparison of the proposed design and recent examples from the literature.

Ref.	f_1, f_2 [GHz]	CJ	N	FBW [%]	RL	IL	ISO	Vol. $(\cdot 10^2)$	Q_u	FoM$_1$ $(\cdot 10^2)$	FoM$_2$ $(\cdot 10^{-4})$
[5]	1	None	4	16	>19	0.72	>50	9.2	–	2.32	–
	1.8		4	6	>19	0.55	>50				
[6]	4.73	None	2	0.51	>21	0.7	>31	2.6	1500	1.28	11.7
	5.03		2	0.48	>21	0.9	>31				
[9]	0.77	RSJ	4	22.3	20	0.6	28	0.5	–	0.12	–
	0.92		4	8.7	20	0.6	28				
[12]	1.54	TJ	3	2.7	22	0.2	–	7.0	2000	2.34	8.5
	1.65		3	3.0	16	0.3	–				
[32]	1.88	RSJ	10	3.7	22	–	–	–	–	–	–
	1.96		9	3.42	22	–	–	–		–	
[37]	1.74	TJ	8	5.63	22	–	80	23.3	–	2.92	–
	1.87		8	5.76	22	–	80				
[38]	2.52	RSJ	5	3.57	22	0.6	–	8.9	2000	1.79	11.2
	2.67		5	3.67	22	0.6	–				
[39]	1.52	None	2	0.85	14.5	0.8	33	1.6	–	0.78	–
	1.64		2	1.1	14.0	0.5	33				
This paper	1.575	RSJ	5	2.0	19.4	1.65	59.3	2.3	925	0.47	19.8
	1.621		5	2.0	19.4	1.70	57.4				

Abbreviations: f_1, f_2 – center frequencies, CJ – coupling junction, RSJ – resonating star-junction, TJ – T-junction, FBW – fractional bandwidth, Vol. – volume, $\mathrm{FoM}_1 = \mathrm{Vol.}/N(\lambda^3)$, $\mathrm{FoM}_2 = Q_u/\mathrm{FoM}_1(\lambda^{-3})$, wavelength λ – the one at $\sqrt{f_1 f_2}$

While proving to offer comparable performance in terms of key indicators, such as RL and ISO, the diplexer proves to be one of the most compact solutions, with a volume of $0.023\,\lambda^3$. In particular, the normalized volume divided by the number of resonators is as low as $0.47 \cdot 10^{-2}\,\lambda^3$, representing one of the lowest values among those reported. Additionally, the ratio between the unloaded quality factor and the normalized volume reaches up to $19.8 \cdot 10^4\,\lambda^{-3}$, making it the highest value available in the literature.

The simple geometry, combined with the Y-shaped junction, the same dimensions for the two channels and an all-metal design make the device easy and cost-effective to manufacture.

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