Extended summary

Design of High Frequency Reconfigurable Components for Space and Defence Applications

Curriculum: Electromagnetics and Bioengineering

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Abstract. From a system point of view, although fully-customized components guarantee performances optimization under certain operating conditions, the capability to cover several different functionalities according to the changing environment represents a key feature in actual systems and architectures. Reconfigurable components, characterized by high flexibility, reliability and maintainability levels, represent then the main building blocks for adaptive and multi-functional architectures.

This Ph.D. work has been focused on the investigation and development of new architectures, circuit topologies and geometries of passive components in order to obtain physical structures that, in combination with commercial tuning elements, are suitable for the realization of high frequency reconfigurable components addressed to different applications: starting from the design of frequency-agile filters for tactical radios, reconfigurability has been introduced in the case of phased-array antennas for radar applications characterized by inherent frequency selectivity properties; finally, a synthesis procedure for a diplexer prototype with independently tuneable channels has been carried out.

Keywords. Dual-Manifold Feed Diplexer, Filtenna, Frequency Tuneability, Non-uniform resonators, Phased-array antennas

1 Design of High Power UHF Band-Pass Filters with Agile Tuning

In modern radio communication systems based on Frequency Hopping (FH) transmission protocols, in order to prevent Electromagnetic Interference issues and to reduce SNR-level deterioration due to hostile entities and jammers, the availability of sub-components capable to change their performance characteristics very rapidly represents a fundamental requirement. In this perspective, a great interest is devoted to the design of agile tuneable filters, in order to guarantee short switching times between different operating modes through remote control.
The attention has been focused on the band-pass filter which is part of the high power stage of a transmission radio channel. The filter is placed after the power amplifier for the suppression of spurious harmonics that could interfere with the neighbor components: for this reason, it is crucial the achievement of a low Insertion Loss level (less than 1.5 dB). However, the accomplishment of this specification becomes even more challenging since very narrow instantaneous bandwidths (in the order of megaHertz) are required in FH radio transmission applications.
The design of a UHF high power electronically tunable filter, compatible with Frequency Hopping communication techniques, has been carried out. It is based on the use of solid-state tuning elements (PIN diodes and Varactor diodes) combined with TEM non-uniform resonant cavities. The use of this kind of resonators allows to prevent non-linearity issues due to the use of Varactor diodes in presence of high power level signals. An analytical model of a capacitively loaded exponentially tapered transmission line resonator has been developed, allowing to obtain a first estimation of the optimum position for the varactor connection point in terms of RF Voltage and frequency tuneability range. In order to obtain a structure capable to cover a wider frequency tuneability range, hybrid varactor-switched capacitors tuneability has been implemented through the use of fixed capacitors activated through PIN diodes.

2 Reconfigurable Phased Array Antennas with Inherent Frequency Selectivity Properties

Due to the increasing number of sensors and the growing use of wireless equipment on board of modern military platforms, it is crucial for communication and radar systems to avoid spurious interferences. Therefore, band-pass filters are needed both between the antenna and the Low Noise Amplifiers (LNAs) to avoid losses in the receiver sensitivity and in the transmit chain, in order to suppress the emission of harmonic frequency components and to comply with standard regulations for emission outside the operating band.
However, since very demanding specifications in terms of selectivity and out-of-band suppression are required by the overall front-end architecture, these filters are characterized by relatively large physical size, occupying a large fraction of the available surface when used in phased array application with large scanning angle capabilities. At the same time, due to physical and technological constraints, these requirements cannot be met through one single filtering stage implemented in the MMIC module. In view of this, a distributed filtering approach for the overall Tx/Rx chain is usually considered in order to achieve the desired specifications through several filtering stages with more relaxed performances. In this perspective, the integration of the filtering function in the antenna element was recently investigated, focusing on single antennas or non-scanning arrays [1]-[6].

2.1 Integrated filtering and common-mode rejection in a planar phased-array antenna of connected dipoles.

The integration of filtering properties in a planar phased-array of connected dipoles has been investigated. Starting from a classical three-pole Tchebychev prototype, the radiating element, constituted by capacitively-coupled dipoles in an array configuration, realized the first pole of the filter, while the remaining part was implemented in coplanar stripline, as depicted in Figure 1(a).

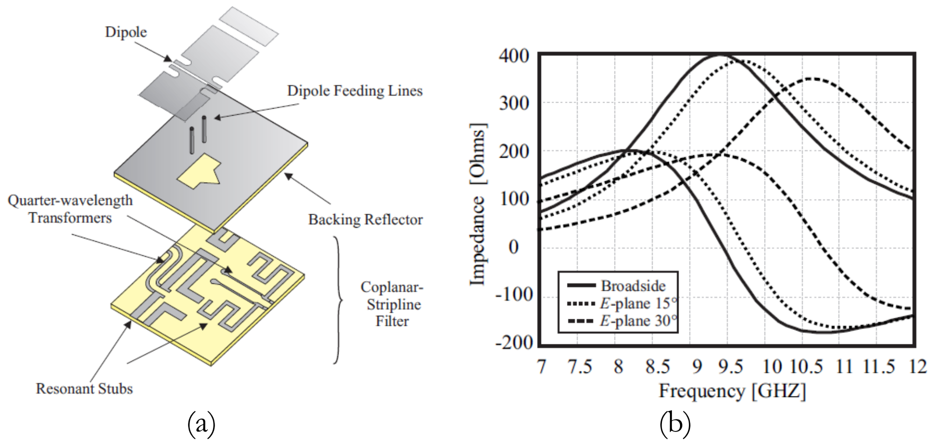

Figure 1. (a) Exploded view of the array unit cell (b) Active impedance of the dipole when scanning on the E-plane.

Since scanning on the E-plane produced a shift towards higher frequencies of the impedance curve of the dipole (Figure 1(b)), causing a substantial detuning of the implemented filter, a varactor diode has been added between contiguous elements (Figure 2(a)) in order to compensate the dipole resonance shift, as shown in Figure 2(b).

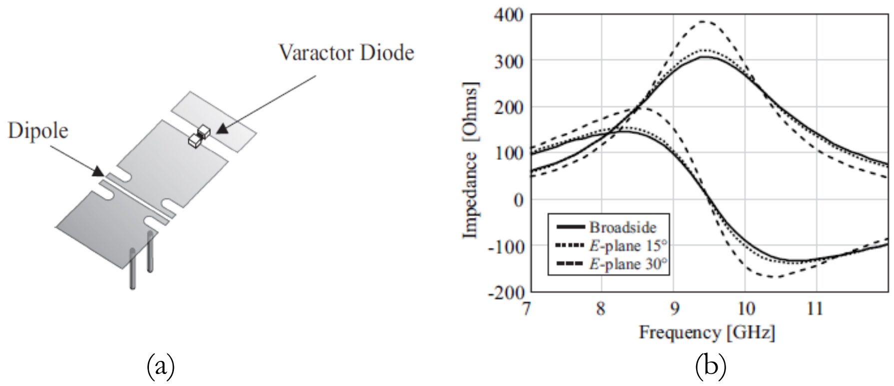

Figure 2. (a) Varactor diode coupling contiguous dipoles (b) Active impedance of the dipole tuned by a varactor diode when scanning on the E-plane.

However, as a result of the full-wave simulations of the overall filtenna structure, the excitation of common-mode resonances when scanning on the E-plane was observed. As highlighted in Figure 3(b), the common-mode resonance peak is clearly visible at about 8.8 GHz for E-plane scan to 15°.

An effective strategy for the common-mode rejection, based on the use of a planar X-band hybrid ring connected to the output port of the filtenna structure, as shown in Figure 3(a), has been implemented. As apparent in Figure 3(c), the active reflection coefficient does not show any resonance peak when scanning on the E-plane.

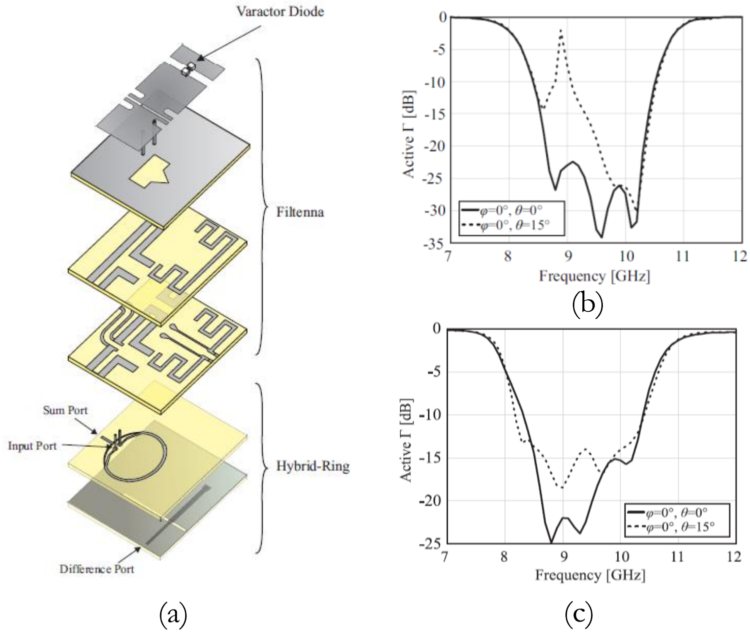

Figure 3. (a) Exploded view of the array unit cell with the Hybrid-Ring connected to the filtenna structure (b) Active reflection coefficient for broadside and E-plane scan to 15° (c) Active reflection coefficient of the combination of filtenna and rat-race for broadside and E-plane scan to 15°.

As a further development, a novel compact desing for the filtenna unit cell has been carried out, where part of the filtering function is still performed by the radiating elements, while the remainder is integrated in the common-mode rejection module itself. As apparent from simulations results, good matching performances have been achieved when scanning up to 30° on the E-plane and up to 45° on the H-plane.

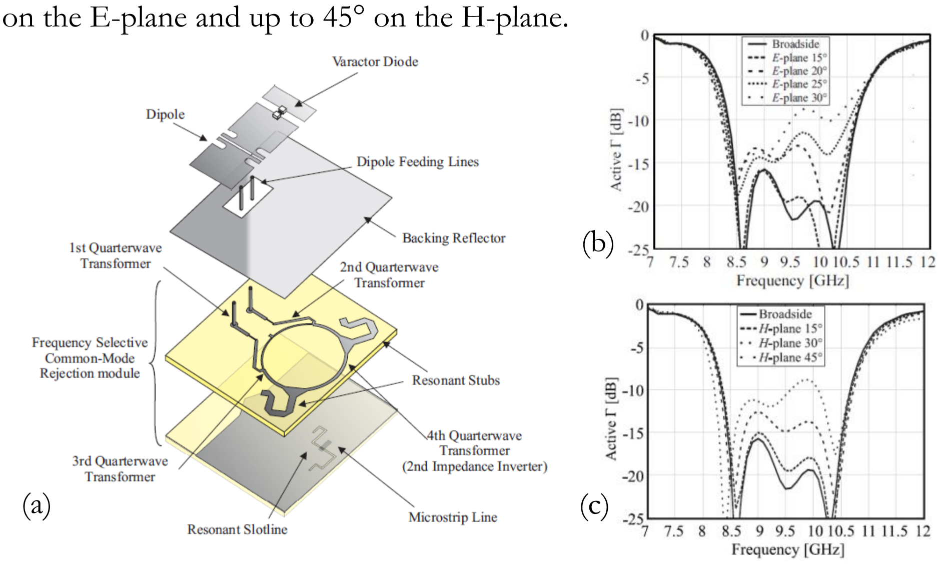

Figure 4. (a) Exploded view of the compact filtenna structure (b) Active reflection coefficient when scanning on the E-plane (c) Active reflection coefficient when scanning on the H-plane.

2.2 Frequency Tuneable Patch Filtenna Array with Spurious Harmonics Suppression

The filtenna concept has been investigated for an X-band phased-array antenna of slot-fed patches. Two main strategies have been considered for the design. In the first configuration, the radiating element, exploiting its resonating behavior in the operating bandwidth, provides the first pole of a Tchebyshev band-pass filter, as shown in Figure 5. The remaining part of the filter, realized in microstrip line, is connected to the output feeding line, placed underneath the ground plane, allowing for high integration and low profile.

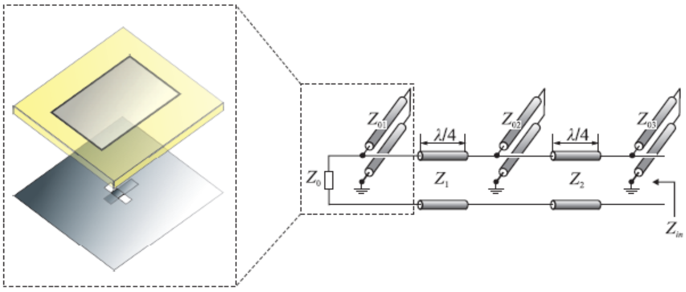

Figure 5. Block scheme of the slot-fed patch filtenna

Good matching performances when scanning up to 45° on both the main planes are achieved with this design configuration. However, instantaneous bandwidth is limited to 10% and spurious rejection mechanisms are not provided.

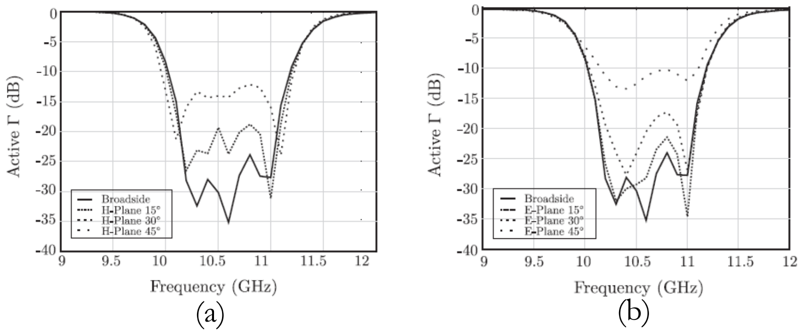

Figure 6. Active reflection coefficient of the slot-fed patch filtenna when scanning on the (a) H-plane and (b) E-plane

According to the second filtenna design strategy, the slot-fed patch antenna is cascade connected with the bandpass filter, as depicted in Figure 7.

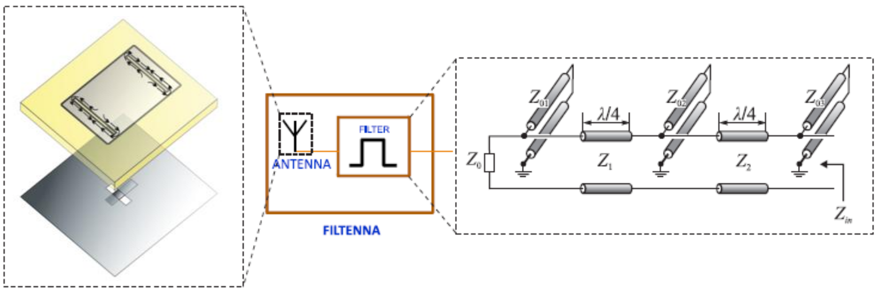

Figure 7. Block scheme of the second configuration of the aperture coupled slot loaded patch filtenna

Furthermore, a rejection mechanism of spurious resonances has been implemented in the radiating element. Specifically, the higher order harmonics of the antenna are detuned by etching slots on the patch surface, inducing a strong alteration of the current paths associated to the high order modes, while fundamental mode is weakly perturbed. Since the 3rd harmonic of the antenna is then shifted with respect to the original frequency, the cascade connection of the radiating element with the filter would result in the mutual suppression of the 3rd harmonic resonances of both the antenna and the filter, as apparent from Figure 8(b).

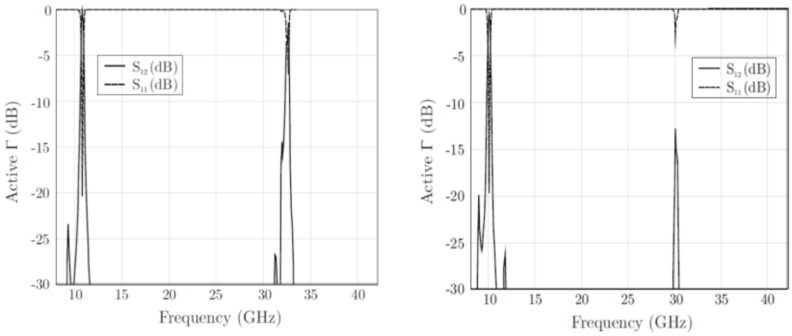

Figure 8. Active reflection and transmission parameters of the (a) aperture coupled patch filtenna array (b) aperture coupled slot loaded patch filtenna array.

Finally, in order to make the antenna capable to cover the entire radar X-band ([8.5 - 10.5] GHz), frequency reconfigurability capabilities have been introduced in the radiating element by connecting the edges of the patch to a bank of fixed capacitors switched through PIN diodes.

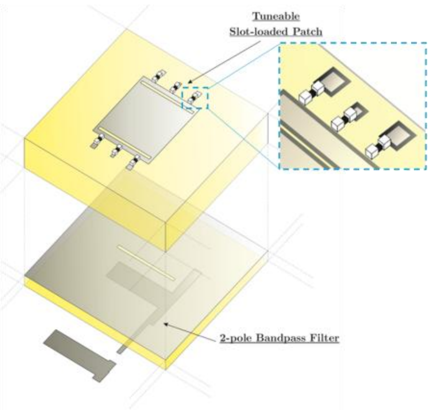

Table 1

PIN activation state	F0 (GHz)	IL @ F0 (dB)	IL @ 3*F0 (dB)
000	10	0.35	20
010	9.6	0.42	28
101	9	0.562	40
111	8.8	0.611	32

Figure 9. Exploded view of the tuneable slot-loaded patch filtenna array unit cell

The performances of the overall structure obtained connecting the tuneable slot-loaded patch antenna with a 2-pole microstrip band-pass filter, as shown in Figure 9, have been evaluated for an infinite array environment. Good performances are achieved in the entire tuneability range, together with high suppression levels (minimum 20 dB) of the 2nd and 3rd harmonic resonances for all the operating states.

2.3 Reconfigurable Diplexer Prototypes for Output Stages of Satellite Payloads.

Reconfigurable diplexers and multiplexers represent key hardware in future flexible payloads: specifically for high power stages, novel concepts that do not rely on circulators or hybrids are needed, overcoming the RF challenges related to channels electrical interactions due to the use of a reciprocal solution. Indeed, the use of such kind of components is not desirable since they introduce large penalties in terms of dissipation losses and passive intermodulation effects.

In view of this, a pioneering work has been proposed by J. D. Rhodes [7]: it consists in a reciprocal dual-manifold feed approach, allowing for independently tuning of all channel filters without the use of non-reciprocal isolating devices. As shown in Figure 10, an additional path is introduced between the common port and the second resonator of each channel filter. The mutual compensation of the two variable reactances produced by each filter allows to reflect on the other channels an all-pass network, preventing a deterioration of the amplitude characteristics when shifting the mid-band frequency of each filter.

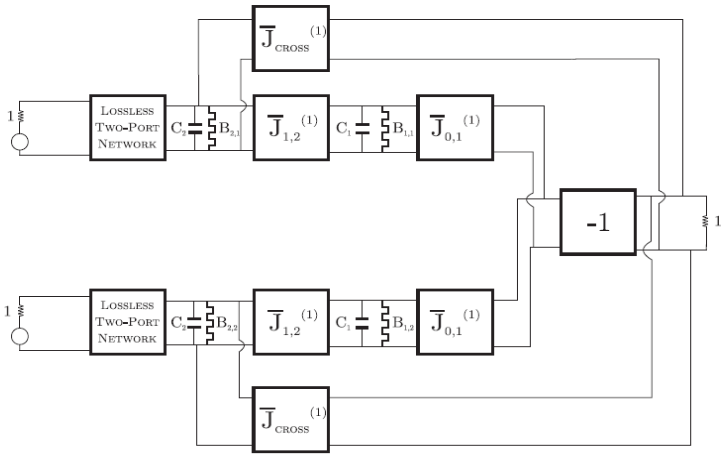

Figure 10. Dual manifold feed diplexer prototype

Rhodes' original prototype has been extended considering filter prototypes made up of identical resonators, allowing to establish a close correspondence with the physical structure. The case of an X-band diplexer having channels with 27 MHz bandwidth (f01 = 11.0 GHz, f02 = 11.030 GHz, Chebyshev Response, RL = 20 , N = 5) has been considered. Common-port return loss and insertion loss performances between each channel input and common-port are highlighted in Figure 11(a). Then, the midband frequency of the upper filterhave been shifted up to 11.8 GHz acting on the resonator parameters (L, C) and not on the couplings. Return loss levels in the operational bandwidths are still maintained for both the channels, as apparent from Figure 11(b).

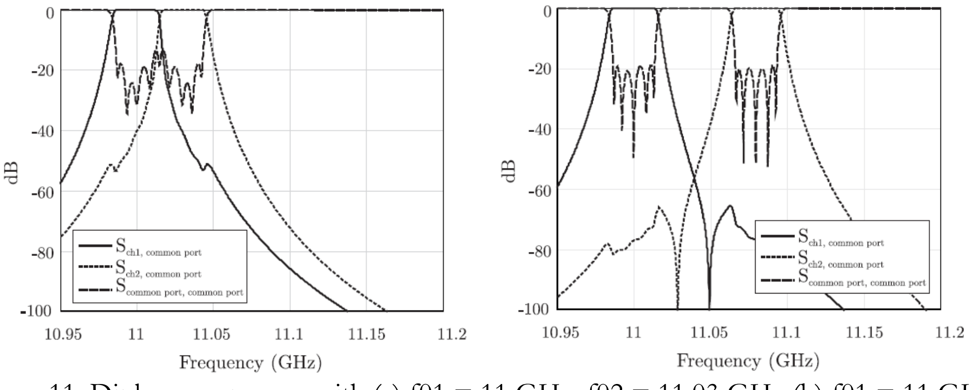

Figure 11. Diplexer responses with (a) f01 = 11 GHz, f02 = 11.03 GHz (b) f01 = 11 GHz, f02 = 11.08 GHz

The validity of the dual manifold concept has been also verified when channel bandwidths are different or in the case of a 3-channel multiplexer, showing good performances in all the considered scenarios.

Furthermore, dual-manifold feed diplexer prototype has been made capable to provide bandwidth tuneability for each channel through the cascade connection of a quasi high-pass and a quasi low-pass filter: bandwidth and mid-band frequency tuneability results from the variation of the mid-band frequency of each of the two filtering stages.

It has been considered the case of a dual-manifold feed diplexer where channel 1 is made up of a band pass filter, centred at 11 GHz with a bandwidth of 27 MHz, cascaded with a band pass filter with the same mid-band frequency and bandwidth. Channel 2 consists of a band pass filter centred at 11.0575 GHz with a bandwidth of 72 MHz, cascade connected with a band pass filter with the same mid-band frequency and bandwidth, as highlighted in Figure 12(a). Then, mid-band frequency of the first filtering section of channel 2 has been shifted to 11.0845 GHz: it results in a variation of the overall bandwidth of channel 2 from 72 MHz to 45 MHz, as shown in Figure 12(b). Furthermore, dual-manifold frequency configuration allows to preserve good matching performances also when shifting the mid-band frequency of the channel filter, together with the bandwidth modification.

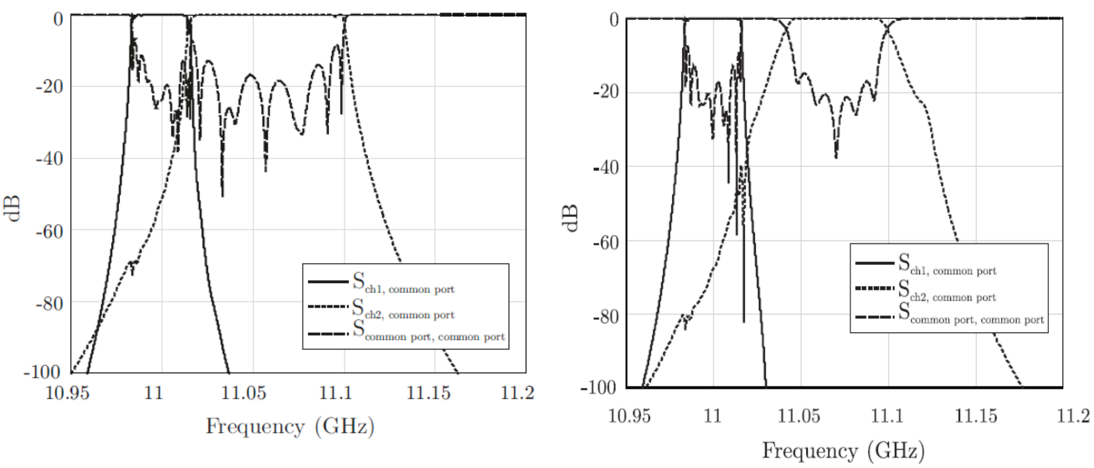

Figure 12. Bandwidth tuneable diplexer where (a) BW1 = 27 MHz, BW2 = 72 MHz (b) f01 = 27 MHz, BW2 = 45 MHz

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