# Filter Technology for Spectrum Management

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***Abstract* — Some recent developments in filter technology at the Naval Research Laboratory will be described and the application of these technologies to spectrum management will be discussed.**

## I. Introduction

Poorly managed spectral output from transmitters can and does cause a variety of problems. In particular, such mismanaged spectral output is increasingly causing interference problems with collocated, nearby, or very sensitive receivers. Recent efforts [1-13] at the Naval Research Laboratory (NRL) to address these problems through improved filter technologies will be described and ways in which these technologies can be applied to manage the spectral output of transmitters and the spectral input of receivers will be discussed.

## II. Fixed-Frequency Filters

The perpetual tension between size, efficiency, and linearity in the design of power amplifiers tends to discourage the design of power amplifiers that generate no unintended signals. Compact, high-power, high-selectivity, low insertion loss filters and multiplexers can be used to clean up unintended spectral emissions and enable power amplifier designs that emphasize smaller size and greater efficiency.

### *A. Compact Ridge-Waveguide Filters and Multiplexers*

Recently, technology for high-power wide-band bandpass filters and frequency multiplexers has been demonstrated that exhibit new levels of compactness and performance [1]-[2]. The contiguous channel filters of the 4-6.25 GHz multiplexer of [1], as described in Figs. 1 and 2, use evanescent-mode-coupled ridge-waveguide resonators to realize a small filter volume while maintaining high power handling and wide upper-stopband bandwidth. The multiplexer manifold also employs ridge waveguide and couples to the individual channel filters through shunt inductive irises to achieve an even more compact volume and a footprint convenient for use in array applications. Typically, the design of such an advanced and complicated multiplexer would rely on proprietary techniques and specialized software tools. However, reference [1] provides a thoroughly detailed and relatively simple circuit-model-based synthesis procedure that relies on only general purpose software tools that are readily available from a variety of vendors.

The design of compact multiplexers was extended in [2] by dielectric-loading evanescent-mode-coupled T-profile ridge-waveguide resonators, enhancing their “lumped” nature for further size reduction while preserving their low insertion loss, high power handling, and wide upper stopband characteristics. The 531–1636 MHz multiplexer of [2], shown in Fig. 4 and measuring 375mm x 108mm x 57mm, was used to selectively combine the outputs of two sub-octave-frequency-banded power amplifiers, preserving output signal power while suppressing harmonic and other out-of-band interference.

### *B. Absorptive Notch Filters*

Fixed-frequency bandstop, or “notch”, filters can be used to selectively attenuate known interferers at a receivers input or to prevent transmitters from broadcasting interference within sensitive frequency bands. To assist with such applications, passive microstrip absorptive notch filter technology was introduced in [3] - [5] that enables small, low quality, low cost components to be used to remove interference with high selectivity and exceptional effectiveness. Techniques for synthesizing higher-order absorptive notch filter networks were described in [6] and [7]. Such higher-order absorptive notch filters are capable of achieving equivalent performance to conventional filters in as little as one-tenth the volume.

## III. Tunable Filters and Attenuators

While fixed-frequency multiplexers and bandstop filters can be very effective at removing known interference and protecting fixed frequency bands, advanced communications and electronic warfare systems increasingly require adaptive and reconfigurable solutions to interference issues. Tunable and reconfigurable filters are needed to address these more demanding requirements. Although low-distortion tuning elements are critical components of tunable filters, the focus in this section will be on novel NRL circuit technologies. Despite recent progress in tuning element capabilities – such as the Delft University demonstration [14] of varactor diodes with 9:1 tuning range, OIP3 of 57 dBm, and quality factors of about 50 at 2GHz – significant challenges remain to realizing high-power, low-distortion, high-quality tuning elements.

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## A. Tunable Absorptive Notch Filters

In [4], the size, cost, and performance advantages of fixed-frequency absorptive notch filters were extended to filters with tunable operating frequencies. The unique performance capabilities of this technology were recently demonstrated by a varactor-tuned microstrip absorptive notch filter designed to excise a narrow, reconfigurable, portion of the output spectrum of a wide-band transmitter [2], [8]. This 102mm x 64mm x 9mm filter is shown in Fig. 5, along with its measured performance. Using commercial varactor diodes as tuning elements, the filter maintains a 3MHz-wide stopband attenuation of more than 60dB across a majority of its 480–925 MHz (> 92%) tuning range. Passband insertion loss ranges from 0.7dB to 1.2dB, 3dB-bandwidth remains less than 84 MHz while varying less than 24% over the tuning range, and transition time between operating frequencies is about 720ns. The filter achieves an unprecedented combination of frequency tuning range and speed, electrical performance, and size using only inexpensive commercially-available materials and components.

The advantages of tunable constant-bandwidth microstrip absorptive notch filter technology have also been extended to the realm of lumped-element implementations for lower frequency applications or applications that require even smaller realizations [9].

## B. Frequency-Selective Tunable Attenuators

Receiver front-end amplifiers can be driven into compression or saturation by unexpectedly large high-power signals. Limiters can be used to protect the front-end amplifiers from such signals, but they contribute appreciable broad-band insertion loss and, consequently, degrade the noise figure and dynamic range of the receiver. Recently developed frequency-agile frequency-selective tunable attenuator technology [10], derived from the tunable absorptive notch filter technology described above, offers a low-loss, and more controllable, alternative to limiters in instances when the frequency of offending high-power signals can be determined and when an adjustable level of narrowband attenuation for such signals is desirable. An example of such a device is shown in Fig. 6.

## C. Intrinsically-Switchable Tunable Filters

Tunable absorptive notch filters are most effective at eliminating strong narrowband variable-frequency interference near weak signals of interest, and multiple widely-spaced variable-frequency interferers require multiple filters. However, when the target interference is absent, the notch filters must be removed from the band of interest, either by tuning beyond this band or by using a bypass switch. But, neither approach is desirable. Extending the achievable tuning range of the filters reduces their selectivity when operating within the band of interest, while adding bypass switches adds complexity, cost, and insertion loss.

Tunable bandpass filters are most suitable for capturing weak narrowband signals in an environment with strong broadband interference. However, the passband insertion loss of tunable bandpass filters suffers appreciable and progressively greater degradation with increasing tuning range. To balance conflicting requirements for broader tuning ranges with those for reduced passband insertion loss, designers are often driven to use switched banks of tunable bandpass filters in which individual filters maintain tolerable passband insertion loss by tuning over a relatively narrow frequency range, and the combined tuning range of all of the filters can span the relatively wide frequency band of interest. Unfortunately, the switches used to select the individual filters within the filter bank contribute substantial passband loss themselves, while increasing the size and complexity of the overall assembly.

New intrinsically-switchable tunable filter technology [11], [12] offers an advantageous solution to both the notch filter bypass problem and the switched bandpass filter bank problem. With this technology, the filter is the switch. In both the bandpass and bandstop filter cases, resonator couplings are engineered to provide the desired tuning response. A bandpass filter is made intrinsically switchable by designing it such that the tuning elements used to change its operating frequency can also turn the filter “off” by cancelling the electromagnetic couplings between its resonators (i.e., by balancing the electric and magnetic couplings) [11]. An example of an intrinsically-switchable tunable bandpass filter is shown, together with its measured performance, in Fig. 7 [11]. Similarly, a notch filter is made intrinsically switchable by designing it such that the tuning elements used to change its operating frequency can also decouple its resonators from the through transmission line, effectively reducing the stopband bandwidth to zero and bypassing the filter [12]. A tunable notch filter [12] that illustrates this principle is shown in Fig. 8. Although it was not designed to completely switch into a bypass, or zero stopband bandwidth, state, it illustrates the principle of using the frequency-tuning elements to decouple the resonators and narrow the stopband bandwidth.

## D. Bandstop Filters with an Extended Upper Passband

In broadband transmitters and receivers in which notch filters are needed to eliminate certain undesirable narrowband signals, it is generally necessary for the filters to have broad low-insertion-loss passbands. High-frequency notch filters typically exhibit spurious responses at frequencies above the fundamental filter response (due to the distributed nature of their resonators) that significantly limit the upper passband bandwidth. While such spurious filter responses are difficult to eliminate in fixed-frequency notch filters, they are even more difficult to eliminate in tunable notch filters.

Recently, a new technique has been demonstrated that uses constructive signal interference to cancel spurious filter responses [13]. A fixed-frequency notch filter that employs the technique is shown in Fig. 9 and has a spurious free passband that extends more than 9 times beyond its fundamental 54 dB attenuation notch response [13]. A tunable notch filter with a 56% frequency-tuning range is shown in Fig. 10 and has a spurious free passband that extends more than 5.7 times beyond its fundamental 10 to 22 dB attenuation notch response[13].

## IV. CONCLUSION

Multiple examples of new fixed-frequency and tunable filter technologies from NRL have been described. These technologies offer substantial advantages over conventional approaches and significant opportunities for improved spectrum management by both receivers and transmitters.


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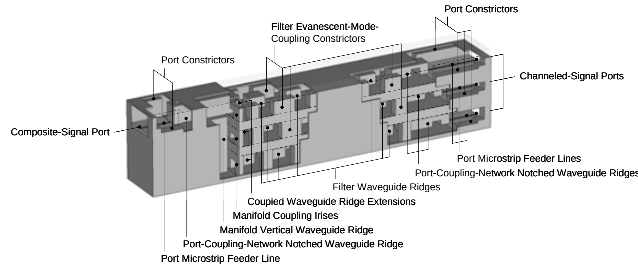



Fig. 1. Annotated rendering of the three-channel, contiguous-band, ridge-waveguide frequency multiplexer example, with portions of waveguide enclosure removed for visualization of internal detail and contours of partially cutaway metal features indicated with dashed fine lines [1].

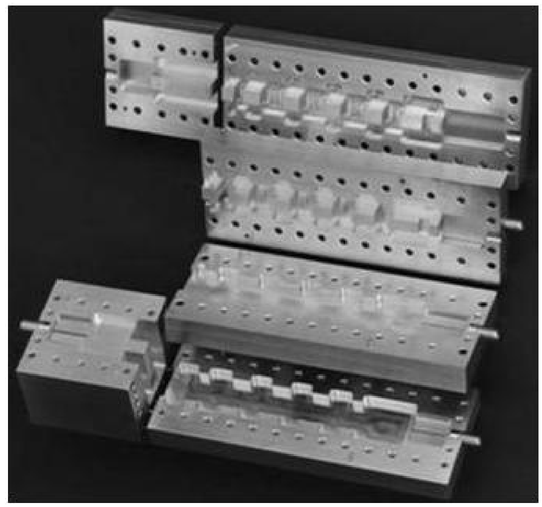


Fig. 2. Experimental three-channel ridge-waveguide manifold frequency multiplexer, partially disassembled (left) and fully assembled (right), 246.0 mm in length, 47.6 mm in width, and 48.2 mm in height [1].

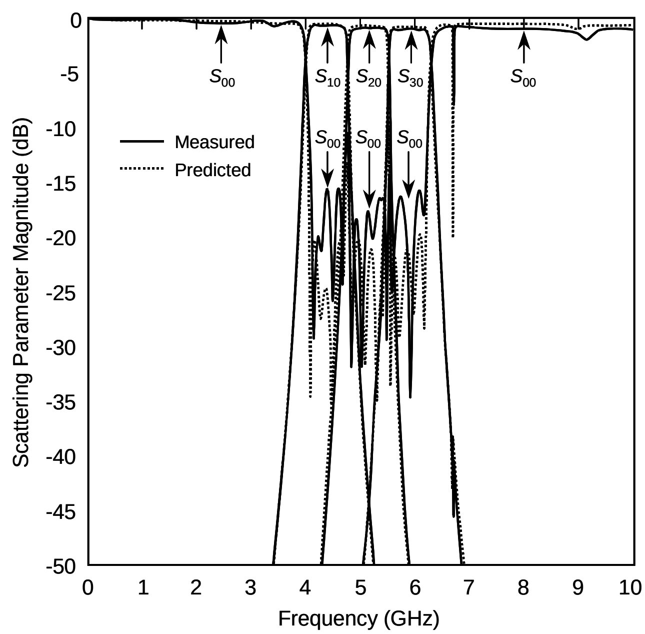



Fig. 3. Measured and predicted responses of the experimental three-channel frequency multiplexer, with equal-bandwidth channels centered at 4.375 GHz, 5.125 GHz, and 5.875 GHz [1].

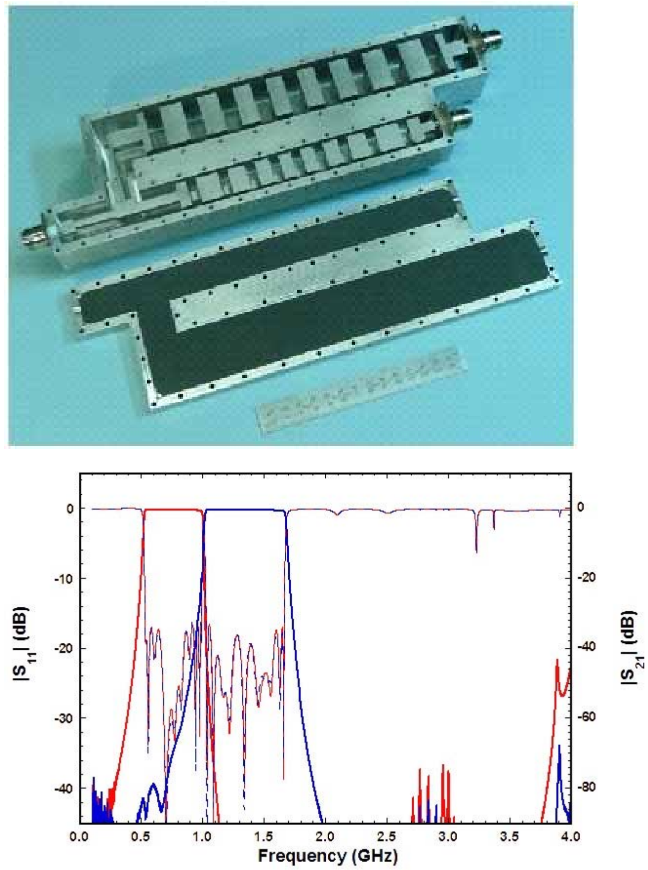



Fig. 4. Photograph of the 531–1636 MHz, partially disassembled, two-channel ridge-waveguide frequency multiplexer and a plot of the multiplexer's measured transmission and reflection characteristics [2].

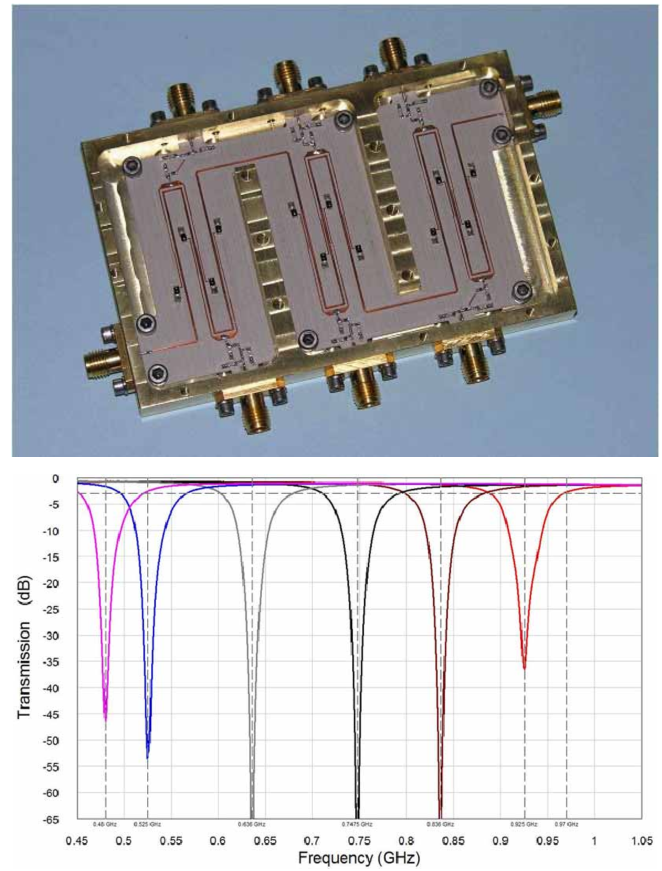



Fig. 5. Photograph and measured transmission characteristic of the sub-microsecond-tunable microstrip absorptive notch filter with a 480–925 MHz (more than 92%) tuning range, tuned to six different operating frequencies: 480, 525, 636, 747.5, 836, and 925MHz [2], [8].

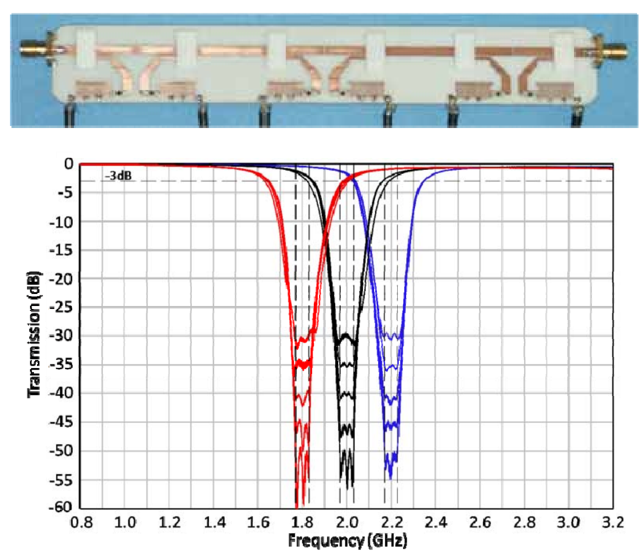
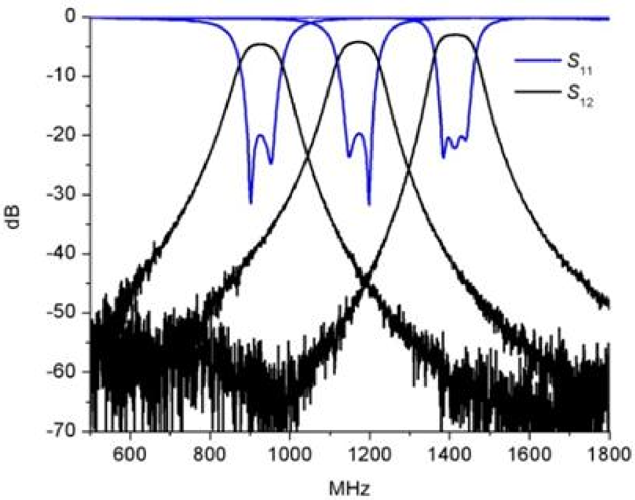
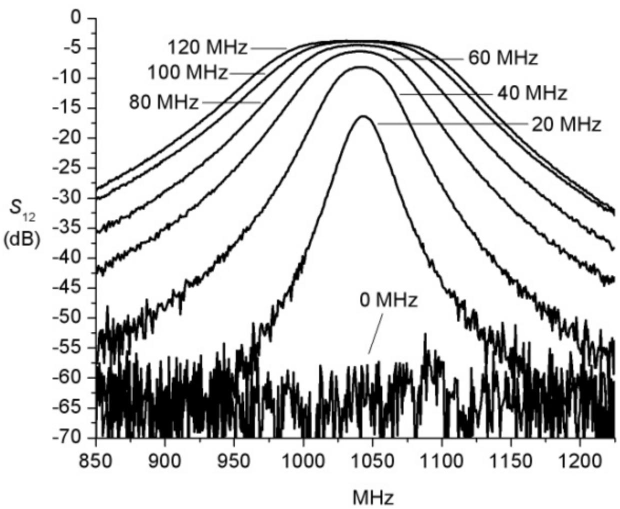



Fig. 6. Photograph and measured response of the frequency-selective tunable attenuator, tuned in 5-dB attenuation steps at 3 different center frequencies: 1.8, 2.0, & 2.2 GHz [9].

(a)




(b)




(c)

Fig. 7. Intrinsically-switchable 3rd-order bandpass filter with tunable center frequency and bandwidth [11]: (a) varactor-tuned microstrip circuit, (b) measurements showing center frequency tuning with bandwidth set to 100 MHz, (c) measurements showing bandwidth tuning and intrinsic switching with greater than 60dB isolation in the OFF (0 MHz bandwidth) state.

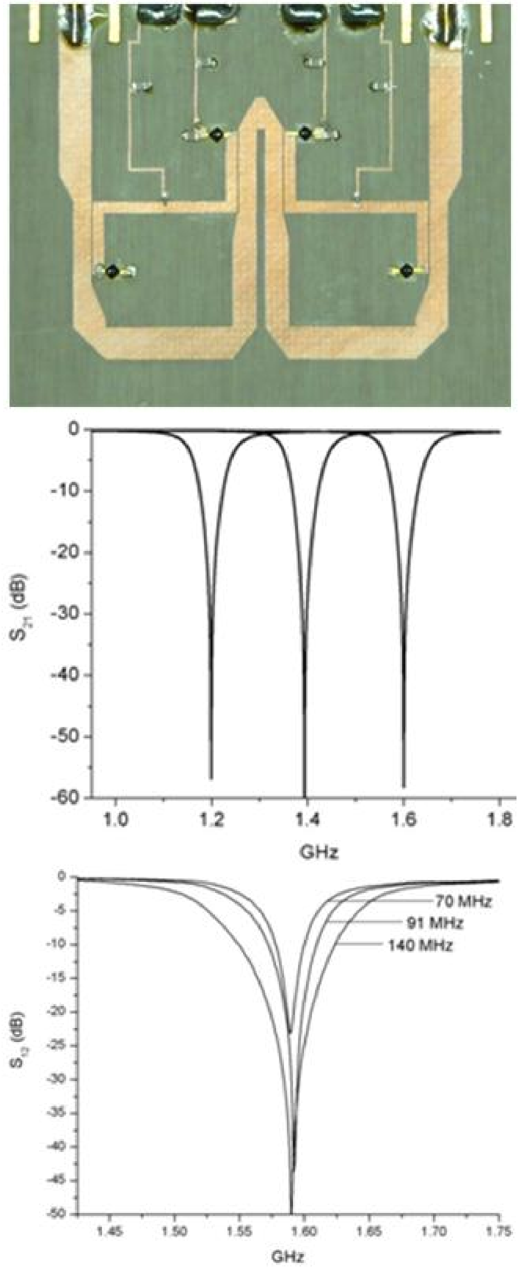



Fig. 8. Photograph of a tunable 2nd-order absorptive notch filter, together with measurements of its center frequency tuning, with its 3dB-bandwidth set to 100 MHz (on the left), and its bandwidth tuning obtained by differentially tuning the varactors (on the right) [12].

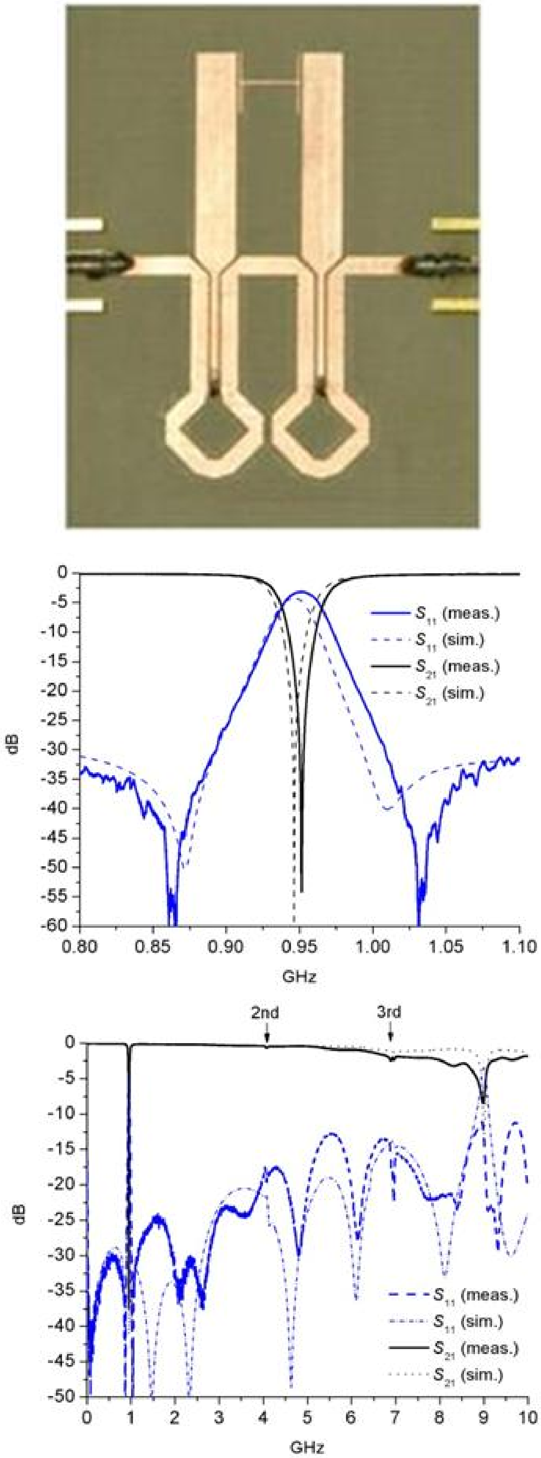



Fig. 9. Photograph and narrowband and broadband measured response of the fixed-frequency microstrip notch filter with 54dB stopband attenuation and upper passband extended to 9 times the fundamental notch frequency [13].

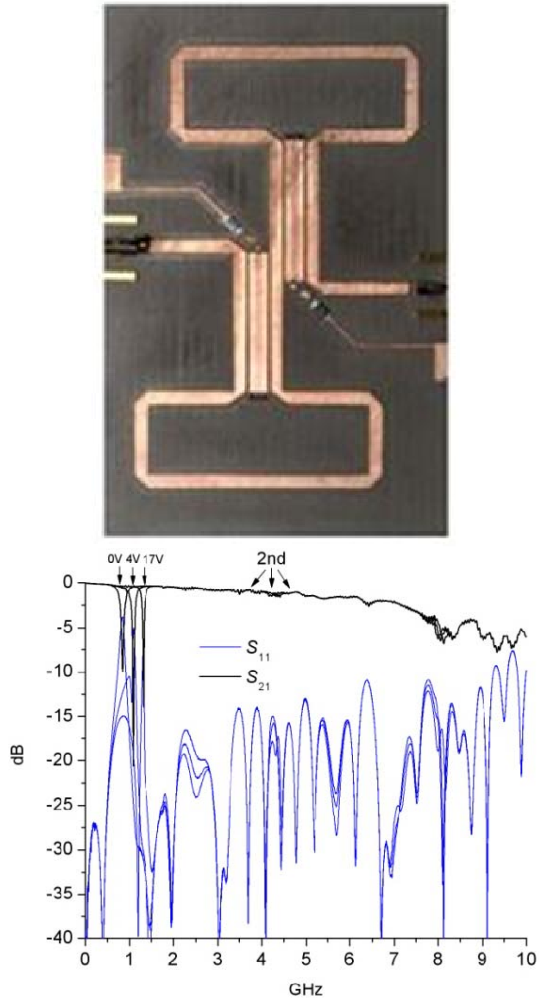



Fig. 10. Photograph and measured broadband response, at three different varactor tuning voltages, of the microstrip varactor-tuned notch filter with 10 to 22 dB stopband attenuation and upper passband extended to more than 5.7 times the fundamental notch frequency [13].