HIGH SPEED VARACTOR TUNED NOTCH FILTER

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ABSTRACT

A design procedure for a varactor tuned notch filter is presented. The filter provides speed and agility required for ECM applications where a large interfering signal must be suppressed. The circuit is based on a varactor tuned microstrip resonator which is edge coupled to the signal transmission line. A three stage filter is described which tunes to any frequency between 1070 and 1240 MHz in less than 5 microseconds. It has a 1 dB bandwidth of 100 MHz, a 20 dB bandwidth of 20 MHz, and an RF power capability of 10 mW.

INTRODUCTION

In filter applications where a high speed electronic tunability is of interest, varactor diodes provide tuning times in the microsecond range as compared with milliseconds in the case of YIG tuned resonators. Varactors provide miniature size and low cost, and their performance continues to improve as higher quality factors are attained. In this paper, the analysis and design of a class of varactor tuned microstrip notch filters is presented for applications where tracking and suppression of a jamming signal is of interest.

Applications of varactors in the tuning of bandpass and bandstop filters are discussed by Hunter and Rhodes in [1] and [2]. Hunter and Rhodes use a suspended stripline resonator that is coupled at one end to the main signal to produce a notch filter. The resonator is more than a quarter wavelength long and very large ground plane spacing is required to get sufficient coupling with reasonable spacing. In the present work, a varactor tuned microstrip resonator is edge coupled to the signal line. The resonator is smaller than a quarter wavelength and the spacing is about 10 mils for a 25 mil thick substrate. This approach leads to small size, design flexibility, and ease of construction.

DESCRIPTION AND THEORY OF THE FILTER

Consider the circuit in Fig. 1(a) where a transmission line, which is terminated with a matched source and load, is edge coupled to a transmission line resonator. The resonator has a short circuit at one end and a varactor shunted to the ground at the other end. Resonance occurs when the capacitive reactance of the varactor matches the inductive reactance of the resonator line, which has an electrical length of less than 90 degrees. The interaction between the two lines creates a stopband centered at the resonant frequency which can be varied by changing the varactor capacitance, C. Coupling of several simultaneously tuned resonators with the same signal line as shown in Fig. 1(b)

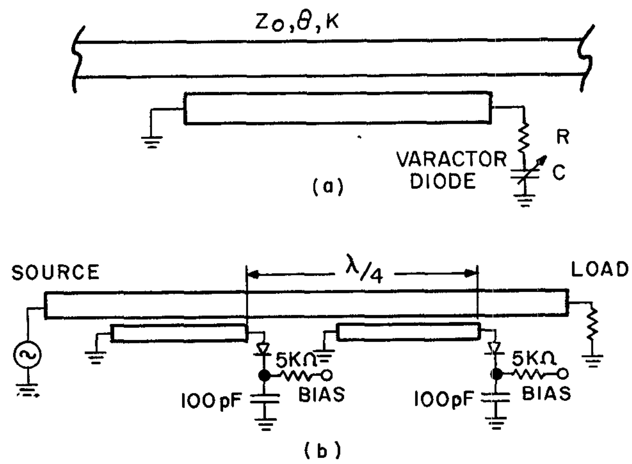

Fig. 1 Varactor tuned resonator notch filter.
(a) Single resonator section.
(b) Two stage resonator configuration with biasing circuit.

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results in a multistage filter with a larger stopband attenuation.

If the parallel lines are approximated by an ideal coupler with a coupling factor, k, the following transcendental equation can be derived for the resonant frequency, (see Appendix).

$$(1) \quad \omega \cdot C \cdot Z_0 \cdot \mathrm{Tan}(\omega \ell / v) = \sqrt{1-k^2}$$

The electrical length, θ , is defined as

$$(2) \quad \theta = \omega \ell / v$$

in a line with a velocity of propagation of v and a physical length of ℓ .

The important bandshape requirements for a typical application of a tunable notch filter are: 1.) the bandwidth at a specified rejection level (for example, 20 dB), and 2.) an upper limit for the bandwidth at the edge of the notch (for example, 1 dB). These requirements can be achieved most efficiently by having resonators with the highest possible unloaded Q. The loss per cycle and stored energy can be computed and used to derive an expression for the unloaded Q of a resonator:

$$(3) \quad Q_0 = \left[\frac{2 \cdot R}{Z_0 \cdot (\theta + \theta \cdot \mathrm{Tan}\theta + \mathrm{Tan}^2\theta)} + \frac{\lambda \alpha_c}{\pi} \right]^{-1}$$

where λ and α_c are the wavelength and the attenuation constants of the transmission line resonator and R is the diode series resistance. It should be noted that the quality factor increases with an increase in the electrical length of the resonator.

TUNING CHARACTERISTICS AND DESIGN PROCEDURE

Starting with Eq.(1), the relative tuning range, $\Delta\omega/\omega_0$, can be related to the varactor capacitance ratio, ρ , and the midband electrical length, θ_0 , as follows:

$$(4) \quad \frac{\mathrm{Tan}[\theta_0(1+\Delta\omega/2\omega_0)]}{\mathrm{Tan}[\theta_0(1+\Delta\omega/2\omega_0)]} = \rho \cdot \frac{(1-\Delta\omega/2\omega_0)}{(1-\Delta\omega/2\omega_0)}$$

The graph shown in Fig. 2 was obtained from a numerical solution of the above equation. For a specified tuning range and maximum available capacitance ratio, Fig. 2 gives the electrical length required for maximum Q.

Limitations on the available capacitance ratio are set by several factors. First: varactors with the highest capacitance ratio, for example

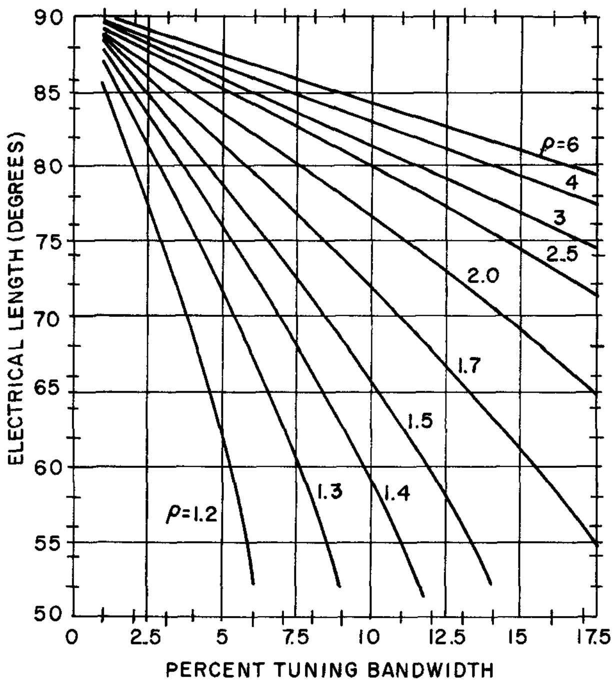

Fig. 2 Resonator tuning design curves (the parameter is the varactor capacitance tuning ratio).

hyper-abrupt varactors, have high series resistance and this limits the Q of the resonator. Second: as the RF power increases, frequency detuning results from RF voltage rectification and this prevents the use of small bias voltages where the largest capacitance change takes place. Fig. 3 shows measured frequency deviation, versus bias voltage, produced by a change in the RF input power from 0.1 mW to 10 mW. Third: the largest bias voltage is limited by reverse breakdown. Considering the above limitations, the maximum capacitance ratio for a typical case is about 2:1. The remaining design parameters for the resonator can be found from equations presented in the Appendix. The value of the coupling coefficient, k, and the number of cascaded stages can then be chosen to achieve the desired bandshape.

EXPERIMENTAL RESULTS

A tunable filter was to be designed to tune over the frequency range from 1070 to 1240 MHz (a 15% range). The notch was to have a 20 dB bandwidth of about 20 MHz, and the 1 dB bandwidth was not to exceed 120 MHz. Three stages were used with 15.5 dB coupling (k=0.16) to achieve this goal.

Best results were obtained with gallium arsenide diodes with a breakdown voltage of 45 volts and a cut-off

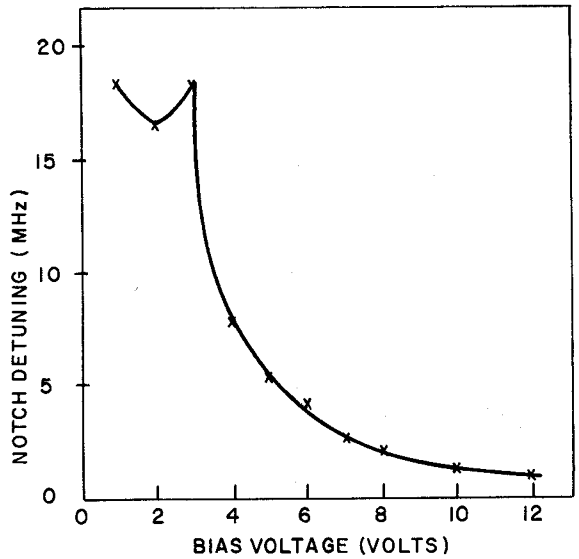

Fig. 3 Frequency detuning for change of input power from 0.1 to 10 mW.

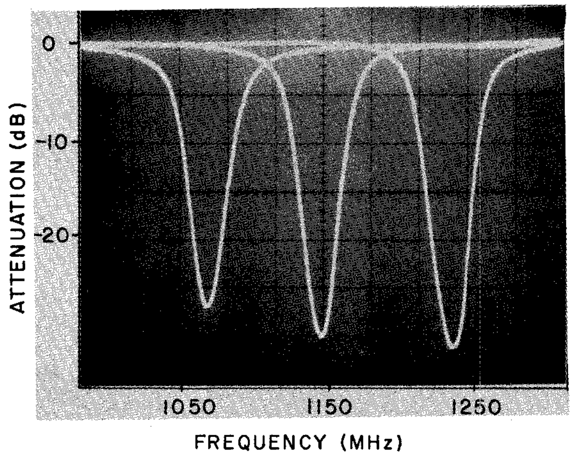

Fig. 4 A multi-trace photograph of three notch filter responses on a scalar network analyser screen.

frequency of 200 GHz at 4 volts bias. Calculations showed that with 10 mW of RF input power a bias range of 7 to 40 volts would minimize the effect of power detuning. This voltage range provides a capacitance tuning ratio of 2:1. The electrical length was determined to be 68 degrees using the graph in Fig. 2. The physical length of the resonator and capacitance of the varactor were found using Eqs.(1) and (2).

The circuit was realized in microstrip with a 25 mil thick substrate and a dielectric constant of 10.5. The centers of the resonators were spaced a quarter wavelength apart. Fig. 4 shows a multi-trace photograph of the filter's response with its notch tuned to three distinct frequencies. Fig. 5 shows the frequency tuning curve, and Fig. 6 shows the 1 dB and 20 dB bandwidths over the tuning range. In each of these measurements, the data and theory agree to within 5% or better. The frequency is specified by a nine bit input word. A D/A converter and driver circuit then control the frequency with an accuracy of 2.5 MHz and a tuning speed of 5 microseconds.

Experiments show that the notch can be totally eliminated by introducing a small forward bias current (about 1 mA) to the varactor. This result is useful for cases in which a broad tuning range is needed. Several filter sections with different tuning ranges can be cascaded on the same signal transmission line. Then, by proper driver design, the resonators can be engaged one at a time to produce continuous tuning across the combined frequency range.

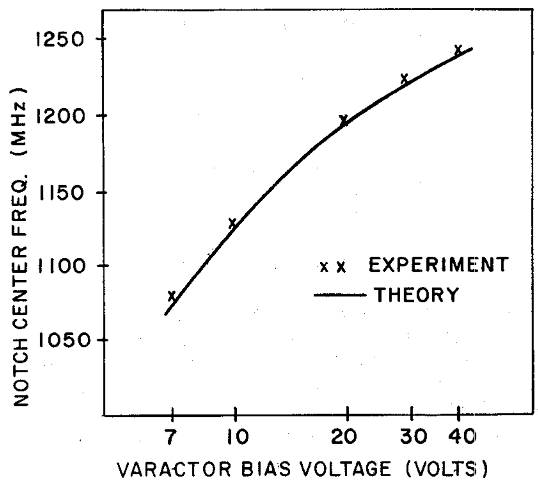

Fig. 5 Notch filter tuning curve.

APPENDIX : FREQUENCY RESPONSE EQUATIONS

The performance of a resonator (see Fig. 7) can be computed directly from the S-parameters of the coupler and the reflection coefficient of the diode terminating it. A symmetrical matched coupler has only two distinct S-parameters:

$$\text{(A1)} \quad \alpha = \sqrt{1-k^2} / (\sqrt{1-k^2} \, \mathrm{Cos}\,\theta + j \mathrm{Sin}\,\theta)$$

$$\beta = jk \cdot \alpha \cdot \mathrm{Sin}\,\theta / \sqrt{1-k^2}$$

where k is the coupling coefficient, and $\theta = \omega \ell / v$ is the electrical length.

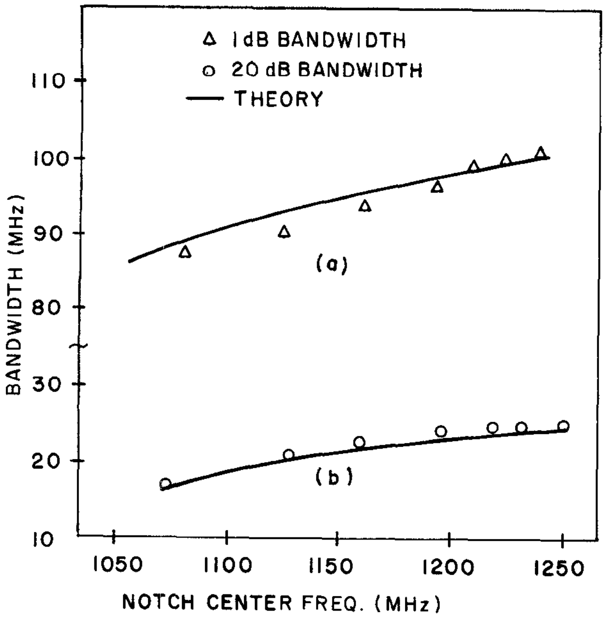

Fig. 6 Rejection band-shape
(a) 1 dB bandwidth
(b) 20 dB bandwidth

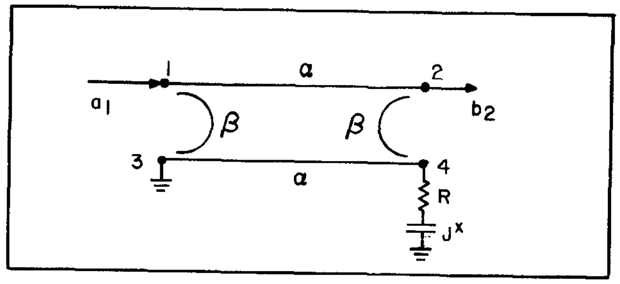

Fig. 7 Resonator nomenclature

With a source connected at port 1, the incident voltage amplitudes are A1, A2=0, A3=-B3, and A4=$\gamma\cdot$B4, where

(A2) $\gamma = (R-Z_0+jX)/(R+Z_0+jX)$

is the reflection coefficient at the varactor port. In this treatment the coupler loss has been lumped together with the varactor loss and represented by the resistor, R. The varactor reactance, $X=-1/\omega C$, varies with the bias voltage and controls the tuning.

Based on this discussion, and reference to Fig. 7, the scattered voltages are determined as follows:

(A3) $B1=\beta\cdot A3 \quad = -\beta^2 A1/(1+\alpha^2\gamma)$

(A4) $B2=\alpha\cdot A1+\beta\cdot A4= \alpha\cdot A1[1-\beta^2\gamma/(1+\alpha^2\gamma)]$

(A5) $B3=\beta\cdot A1+\alpha\cdot A4= \beta\cdot A1/(1+\alpha^2\gamma)$

(A6) $B4=\alpha\cdot A3 \quad = \alpha\beta\cdot A1/(1+\alpha^2\gamma)$

The tuning curve relating notch frequency and varactor capacitance is most easily derived in the limit of zero loss (R=0). In this limit the rejection becomes perfect so that the tuning condition is determined by setting B2=0. The result obtained from Eqs.(A1), (A2) and (A4) is:

(A7) $C = \sqrt{1-k^2}/\omega Z_0 \mathrm{Tan}(\omega \ell/v)$

The capacitance of an abrupt junction varactor varies with the back bias in the following way:

(A8) $C = C_0/\sqrt{1+V/\phi}$

where ϕ =1.2 volts is the barrier voltage and C_0 is the zero bias capacitance. Eqs.(A7) and (A8) then yield the capacitance and bias required to tune the notch to a particular frequency. The shape of the notch can now be computed by substituting Eqs. (A1),(A2), and (A6) into (A4).

As a final point, the peak RF voltage developed across the varactor is equal to the sum of the incident and reflected amplitudes, A4 and B4.

(A9) $V_{RF} =((1-\gamma_0)^2 +4\gamma_0 \mathrm{Sin}\theta)^{1/2} A1/\gamma_0 k\ \mathrm{Sin}\theta$

This tends toward a constant minimum in the limit of zero loss (=1).

(A10) $(V_{RF})\mathrm{min} = 2\cdot A1/k$

The computed value of (v_{RF})min is 10 volts for 10 mW of input power and Z_0=50 ohms (A1=1 volt). This value is consistent with the measured results shown in Fig. 3.

ACKNOWLEDGMENTS

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[1] I. C. Hunter, J. D. Rhodes, "Electronically tunable microwave bandpass filters," IEEE Trans. Microwave Theory Tech., Vol. MTT-30, Sept. 1982, pp 1354-1360.

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