Miniature Superconducting Filters

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Abstract—**Because of the intrinsic low loss of high temperature superconductors at microwave frequencies it is possible to reduce the size of filters while still retaining excellent performance. In order to accomplish this reduction in size new filter geometry is required. Under this theme of miniaturization a number of new and novel types of microwave filter are discussed, this includes delay line filters, lumped element filters and filters based on slow wave structures. Each of the filters are constructed out of high temperature superconductors (HTS).**

I. Introduction

The development of microwave applications of high temperature superconductors since their discovery in 1986 has been extremely rapid and a number of highly sophisticated subsystem level modules have been generated. Many of these are discussed in this issue. Although one way to use these new materials is just to use conventional microwave filter designs and replace the copper circuits by superconducting circuits, this does not exploit the full potential of the superconducting medium. Many novel, new components have been designed and demonstrated using superconductors in the last few years and there is a wealth of research still to be done. This paper discusses some novel components and is organized under the theme of miniaturization.

Superconductors can be used in microwave devices in a number of ways. First, the performance of a filter is improved by the use of superconductors in the sense that the insertion loss can be significantly reduced as well as improving the filter roll off and reducing its bandwidth (increasing the Q). An improvement in performance of filters can be achieved by using conventional design techniques and standard filter types, the improvement comes about because of the reduced dissipation due to the low surface resistance of the superconductor. Secondly, filters can be miniaturized. This usually requires a change in geometry of filters and therefore entirely new types of filters become possible when superconducting materials are used in their construction. Improved performance and miniaturization are complementary and reducing the size of a filter generally leads to reduced performance. Superconductors allow a much larger reduction in size as compared with normal metals whilst still giving improved performance. A third reason for using superconductors may be to use their special properties such as the change in internal or kinetic inductance with microwave power or temperature, or to use their switching capabilities.

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TABLE I
Methods of Miniaturizing Planar Microwave Filters

1. Use of high dielectric constant substrates.
2. Use of internal inductance.
3. Meandering or coiling the transmission lines.
4. Use of slow wave transmission lines.
5. Use of lumped element components

Miniaturization is accomplished by a change in filter geometry. For example, a waveguide filter can usually be redesigned so that the same functions can be performed by a microstrip filter, this is provided the losses of the material making up the microstrip are low enough. The move from a three dimensional structure to a planar waveguide structure significantly reduces the size of the final filter. It is also possible to reduce planar filters in size by a change in geometry, five methods of accomplishing this are given in Table I.

The first entry in the table clearly reduces the size of a filter by reducing the velocity and hence the wavelength is smaller for any given frequency. Thus distributed element filters have shorter resonator lengths and lumped element filters have a higher capacitance per unit area. The second entry in the table is again based on a velocity reduction, but this time produced by an increase in the inductance of a transmission line, without an increase in the associated capacitance. This increase in inductance comes from the internal fields within the superconductor itself, and to have a significant effect must be emphasized by the use of transmission lines with small external inductances. Such transmission lines have very thin layers of dielectric between the ground plane and the signal line. A number of very small filters and resonators have been made using this technique [1]–[6].

The other methods in Table I are discussed separately in the following text. However, it must be pointed out that in certain limits some may be considered equivalent. For example, as a meander line gets smaller and smaller it can eventually be considered a slow wave structure. This occurs when the meander lengths are much less than a wavelength long. The slow wave transmission line could also be considered to be a lumped element filter. However, it is differentiated from a lumped element filter because of its usage. The slow wave transmission line can be used as a transmission line element when designing filters and conventional distributed element techniques can be used in the design process. Whereas lumped elements need to be considered as separate components in the design of a lumped element filter. The distinction of different miniaturization techniques is only given in order to categorize the discussion.

There is in principle no limit to how small in size a filter can be produced and the limitations in performance are determined by the materials used. Low surface resistance allows filters to be reduced in size whilst still maintaining a reasonable insertion loss. As the filter reduces in size the current density increases for a given input signal, and problems with nonlinearity and intermodulation distortion get worse. The current density will eventually reach the critical current of the superconductor. This limit is further complicated by the variation in current distribution within the filter itself. Currents are peaked at the edges of lines within the filter which can cause current limiting at specific points. By careful design, such peaking in the current can be reduced, but this is usually accompanied by an increase in the size of the filter. The other loss mechanisms in the filter have little effect. Dielectric loss is dependent upon the relative amount of energy storage within the dielectric (as opposed to air) and need not change as the filter reduces in size. In microstrip, for example, there is very little electric field outside the dielectric no matter what the size of the device. Radiation loss in fact reduces as the filter size decreases due to the more confined fields. Other limitations on size reduction may occur due to more practical constraints. The patterning resolution limits the line widths to around a micron in size and the packaging becomes increasingly more difficult because of the tight tolerance required on external components. The mismatch at the connector ports can become the dominant loss mechanism in many low loss miniature filters. Other practical limitations are substrate thickness, although deposited substrates can in principle overcome this problem. Another potential problem with smaller filters is their sensitivity to external influences. For example, as internal inductance becomes more predominant the temperature sensitivity of the centre frequency becomes more of a problem.

The ultimate goal of many of the designs discussed below is not only the design of a high performance single filter but the design of a filter bank or multiplexer. Here the miniaturization is much more important when several devices are to be used together.

II. Reflective Delay Line Filters

A component which uses the coiling or meandering principle for miniaturization is the delay line filter. Fig. 1 shows an example of such a filter, it can be seen that the impedance of the microstrip line varies along the line length, it is this variation which causes the filtering action. Fig. 2(a) shows this in diagrammatic form. The input and output of the filter occur at the same port as shown, and a directional coupler is required in order to separate them. The other end of the line is matched with a 50 Ω load. Each impedance step causes a reflection of the forward propagating wave [propagation paths are depicted in Fig. 2(b)], and passbands

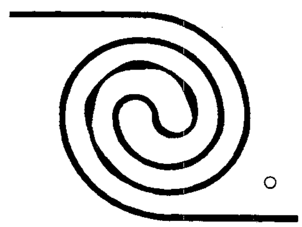


Fig. 1. Single transmission line microstrip delay line filter.

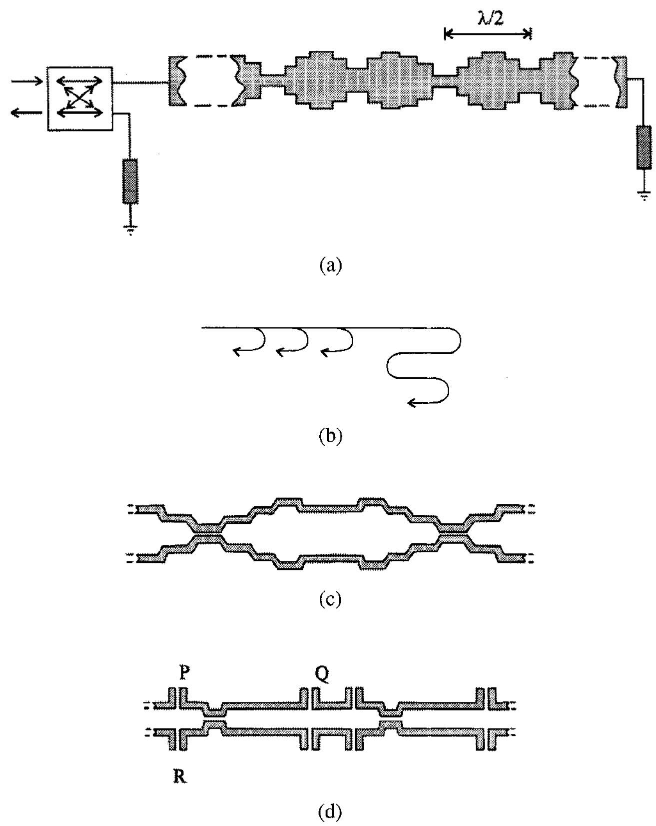


Fig. 2. Delay line filter concepts.

occur when these reflections interfere constructively. Clearly this occurs at frequencies where the local period at some part of the delay line is half a wavelength, since the round trip path difference between groups of reflectors of the same polarity is a wavelength, but the precise response is complicated by multiple reflections between steps. However, a time domain algorithm has been developed [7] to synthesize a wide range of filter responses, including linear phase and chirp; multiple reflections are efficiently allowed for. Frequency dependent loss (such as ω^2 loss dependence for superconductors) and velocity are dealt with, with a suitable convolution. Dual delay line filters [8]–[14] depicted schematically in Fig. 2(c), can also be synthesized using this algorithm. Here the backward propagating wave is generated in the second delay line by a series of couplers; forward and backward waves therefore propagate in separate lines. The leading and trailing edges of the coupler are regarded as separate couplers, and several consecutive steps with reflection coefficients of the same polarity can be generated as shown.

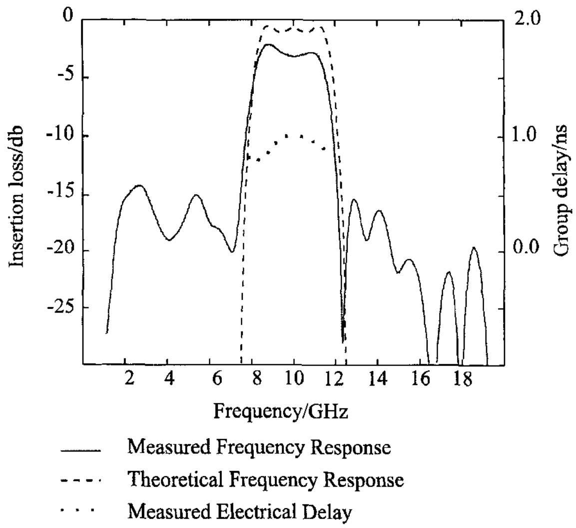


Fig. 3. Frequency response of the HTS microstrip linear phase delay line filter shown in Fig. 1.

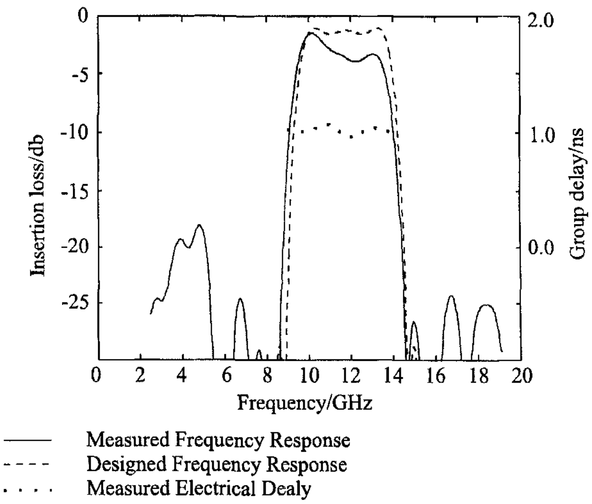


Fig. 4. Frequency response for a HTS linear phase delay line filter using a coplanar line delay line.

For narrow band filters resonant sections can be incorporated within the delay line [15] as shown in Fig. 2(d). A forward propagating wave arriving at Q in Fig. 2(d), is reflected mostly toward P and is forced to make several transits between P and Q before a significant fraction of the power is passed further; greatly increasing the delay. A similar reverberation occurs between P and R via the coupler, its amplitude depends on the coupler and it generates a backward propagating reverberation in the second line, analogous to the backward propagating wave in previous structures. In this way narrow-band filters (which usually require large delays) can be produced with short delay lines without resorting to multi-layer or high-resolution fabrication techniques.

The advantages of the single transmission line delay line filter [8]–[14] over the double delay line filter are clear, only a single delay line is required so that a significantly longer delay can be produced on any given substrate. The disadvantage of the filter is that a wideband directional coupler is required to separate the input from the output. The obvious choice is a superconducting directional coupler which occupies the same substrate. In addition the synthesis technique removes the third harmonic and thus the bandwidth of the filter can be increased above 100%. This could be important for some applications when large time bandwidth product devices are required, or simply when processing is required over very large bandwidths.

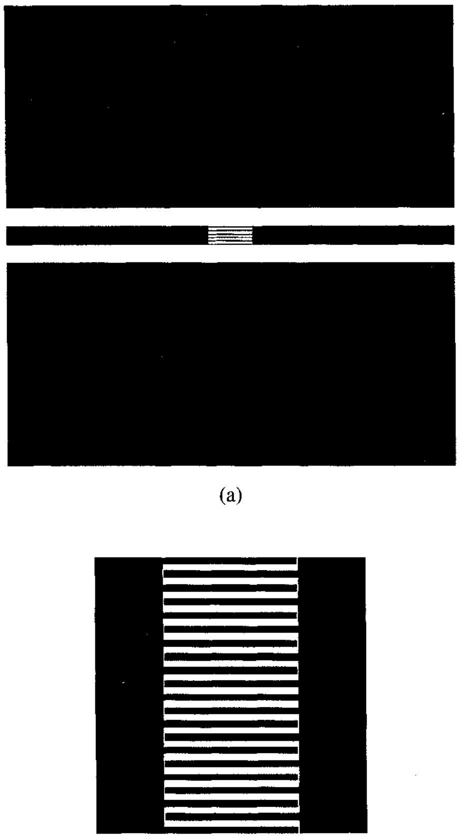
A number of HTS [16], [17] and copper [18], [19] filters have been produced of this type. The frequency response of the filter in Fig. 1 is shown in Fig. 3. The filter is designed to give a linear phase response over a 4 GHz bandwidth centred on 10 GHz [17]. The filter is made of 0.35 μm thick YBCO on a 1 in square, 300 μm thick MgO substrate. Obviously double-sided deposition of the superconductor is required. With this design, delays of only several nanoseconds have been demonstrated to date. The designed and measured responses are shown in Fig. 3. Good agreement is observed across the passband but the sidelobes are high in the stopband. This is due to coupling in the spiral and reflections at the connectors. The difference in the insertion loss between the designed and measured responses is again due to the connections to the device and the difficulty in calibrating the network analyzer at low temperature. It has been found that coplanar lines with not too great a bend radius (in order not to stimulate the slotline mode) can be used for reduction of crosstalk. This is because line widths can easily be made smaller without reducing the thickness of the substrate. A coplanar device with similar specifications as the filter above showed improved performance in terms of close in sidelobe levels [17]. The response of this filter is shown in Fig. 4.

III. Lumped Element Filters

Lumped elements are by definition much smaller than the wavelength at which they operate. Hence, at high frequencies, where the wavelength is short, filters based on lumped elements will be physically small. It turns out that where the line widths are limited by the patterning process the centre frequencies of filters are in the several tens of gigahertz range. At these narrow line widths superconductors are able to help overcome the loss associated with the finite resistance of the conductors.

In order to assess the capabilities of lumped element components consider the lumped element resonator show in Fig. 5(b). The resonator consists of a number of interdigital fingers forming a capacitor. The central finger connects both sides of the capacitor acting as an inductor and hence forming a parallel resonant circuit. This circuit can be used to estimate the quality factors available for superconducting lumped element circuits; although different geometry will obviously produce different quality factors. The losses in this circuit come mainly from the inductor because of the high current density on this element.

This structure can in fact be very simply made into a bandstop filter [20] as shown in Fig. 5(a), here the element shown in Fig. 5(b) is placed centrally in a coplanar transmission line. The whole YBCO structure fits on a 1 cm square MgO



(a)

(b)

Fig. 5. (a) Lumped element bandstop filter with (b) showing an enlargement of the central resonant section.

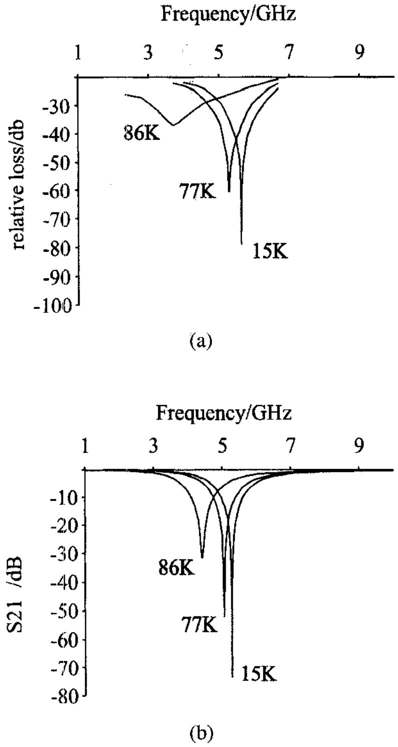


Fig. 6. Bandstop filter performance. (a) The insertion loss at a number of different temperatures and (b) the modeled response.

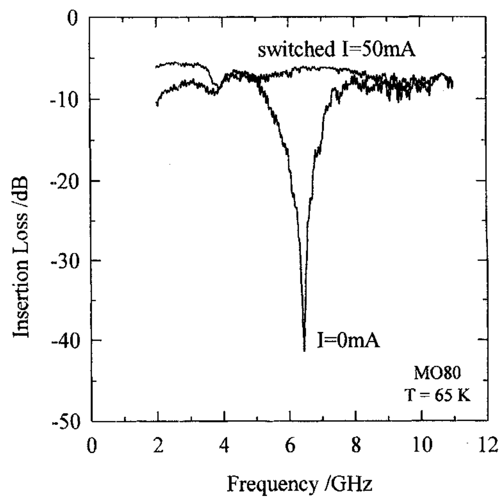


Fig. 7. Lumped element switched bandstop filter.

substrate. In this particular example there are 20 fingers in the interdigital capacitor each with a length of 1 mm and width 10 μm. The coplanar line is 0.41 mm wide with a 0.16 mm gap between the ground plane and central strip.

The frequency response of the filter is shown in Fig. 6(a). The bandstop response is centred at about 5 GHz and varies substantially with temperature. This temperature variation is due to the field penetration into the strip inductor as the superconducting penetration depth alters. Because the film thickness (0.35 μm) is of the order of the penetration depth, these changes can not be taken into account by conventional methods; as the volume current distribution in the inductor needs to be calculated. To model the frequency shift the numerical calculation based on the coupling of multiple transmission lines described in references [21], [22], [23] is used. The results of the calculations are shown in Fig. 6(b). There is a 32% change in resonant frequency between 15 K and 86 K which could be used for tuning the filter by varying the temperature. The stop band performance varies during this temperature range but the maximum stopband rejection is more than 50 dB. The power dependence of the filter is good with only a 0.03% change in center frequency for input power varying from -45 dBm to -10 dBm. The corresponding change in insertion loss is 16% at 15 K and 2% at 77 K.

As mentioned earlier, it is also possible to construct resonators out of this lumped element by leaving capacitive gaps between the resonator element and the feeding coplanar line. Such a resonator made out of YBCO on an MgO substrate has a Q ranging from 9400 at 5.734 GHz and 15 K to 1300 at 5.587 GHz and 77 K [20].

This filter can also operate as a switch. With the application of a bias current the superconducting inductor is turned into its normal state and the resonance which provides the bandstop function no longer occurs; producing an all pass filter. The frequency response of such a switch is shown in Fig. 7 with a 50 mA bias current switching it from its on to off state. The filter/switch is only 1 mm square, and it has almost 40 dB isolation at a temperature of 65 K. The bias current applied for switching corresponds closely with the critical current of the inductor section.

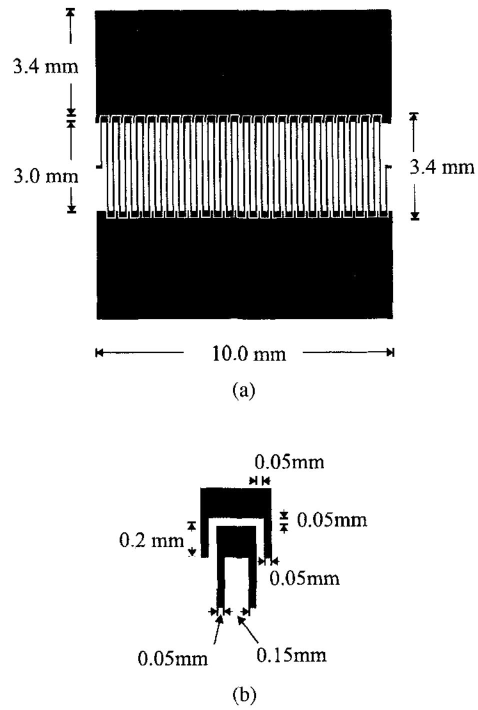


Fig. 8. (a) A coplanar slow wave resonator. The enlargement (b) shows the capacitive portion of the structure.

IV. Filters Based on Slow Wave Transmission Lines

A coplanar slow wave resonator is shown in Fig. 8. It is simply a transmission line formed of discrete inductors and capacitors [24]–[26]. The inductors are the narrow vertical tracks and the capacitance is gained from the narrow gap between the coplanar ground plane and the central conductor. Making a transmission line in this way allows independent reduction in the velocity by increasing both the capacitance and inductance per unit length. Fig. 8 is a device in the form of a resonator, convenient for measuring the slowing of the wave by looking at the resonant frequencies. It should be noted that as the wavelength decreases to around and smaller than the unit cell in the slow wave line, it no longer behaves like a transmission line.

Slow wave structures are not new and some have been used to match the velocity of the optical signal to a microwave modulating signal in electrooptic modulators [27], [28]. Also, considerable work has been done on MMIC's in order to reduce the chip size [29]–[31]. In this case conventional distributed passive elements are at present the limiting factor on the size of MMIC's as the active devices used are much smaller than a wavelength. However, slow wave structures have not generally been used in passive filters because of the associated increase in loss.

The HTS device shown in Fig. 8 is made of thin film $YBa_2Cu_3O_7$ on a 1 cm square MgO substrate and deposited by laser ablation. The length of the resonator is about 10 mm. The fundamental resonant frequency was 1 GHz at 77 K, providing a velocity reduction factor of 15 over the free space velocity. Fig. 9(a) shows the frequency response of the resonator, a large number of harmonic resonances can be seen, they are dispersive as seen by the nonequal frequency difference between each resonance. A cut-off frequency occurs when the wavelength of operation is equal to the length of one period in the structure. The dispersion is complex and is governed not only by the basic response of the inductive and capacitive sections but also by these elements becoming larger in terms of wave length as the frequency increases. In addition coupling between these elements plays a role. Fig. 9(b) shows this dispersion in the form of the velocity reduction over free space velocity as a function of frequency. It can also be seen from Fig. 9(b), that the values of reduced velocity with this coplanar structure are quite large enabling a large reduction in filter size if it is used in a filter structure. Fig. 9(b) also shows a numerical computation of this velocity, in this case no account has been taken of internal inductance effects.

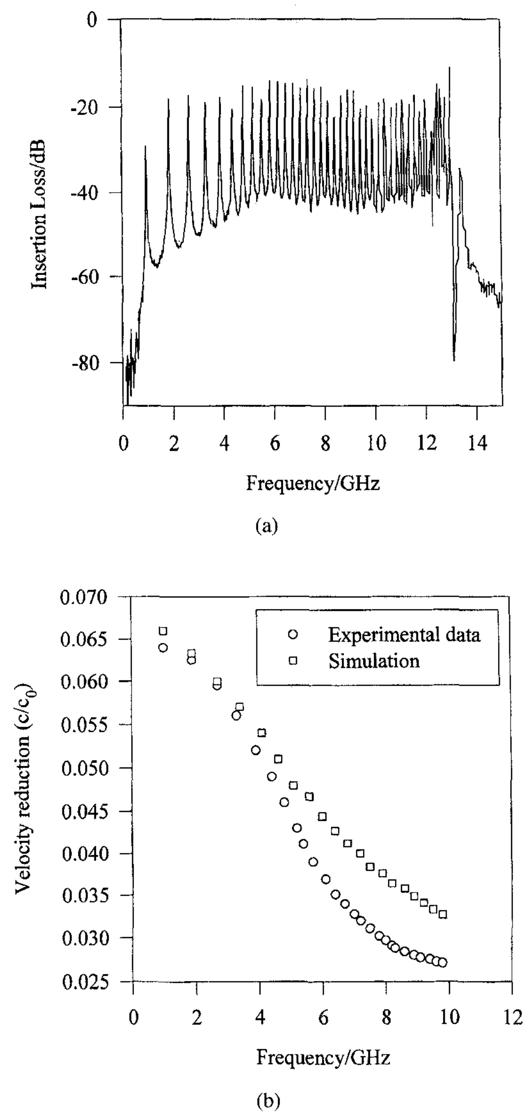


Fig. 9. The performance of the slow wave resonator in Fig. 8. (a) Insertion loss as a function of frequency. (b) Velocity reduction as a function of frequency.

The above geometry is obviously only an example of one method in which discrete inductors and capacitors can be arranged to produce a transmission line. There are many more and each needs to be looked at to see if the velocity can be

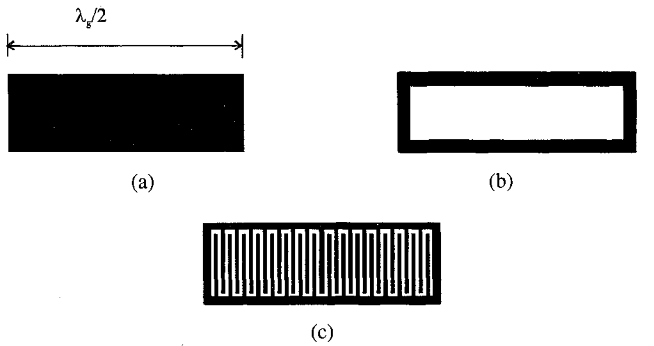


Fig. 10. (a) Conventional half wavelength microstrip resonator. (b) Modified resonator forming a microstrip square loop resonator. (c) Capacitively loaded loop resonator forming a slow wave structure.

minimized given the practical constraints of the patterning and the HTS material. The main use of slow wave transmission line does not necessarily come by making resonators, but by using them as a replacement for conventional transmission lines in conventional filters.

Fig. 10 shows how a similar effect can be achieved using microstrip. Consider the standard microstrip resonator in Fig. 10(a). The effect of removing the central portion to produce the loop of Fig. 10(b) is only small. It effectively turns the standard patch into a loop resonator. The frequency reduction is small as the width of the patch is small compared with its length. To reduce the frequency of the resonator, the loop can be loaded with capacitive fingers as shown in Fig. 10(c). The velocity reduction on this type of transmission line is controlled by the number of fingers within the loop. Copper resonators of this type have shown a 25% reduction in frequency around 4 GHz with 31 fingers in the loop [32]. Coupled resonators have also been demonstrated [33] showing that conventional design techniques can be used to design coupled slow wave lines. A superconducting resonator of this type with outside dimensions 4 by 1 mm and 195 fingers each of 10 μm width and 890 μm long resonates at 10.53 GHz with a Q in excess of 1200 at 77 K. This represents about a 25% reduction in size over the conventional microstrip resonator.

Fig. 11 shows two filters based on the microstrip capacitively loaded loop. One with the standard edge coupled design [Fig. 11(b)] and the other and in line version of the same filter [Fig. 11(c)]. A conventional microstrip filter is shown to the same scale in Fig. 11(a) for comparison purposes. These filters are made of copper to demonstrate the principle and are all centered on a frequency of 3.4 GHz. The frequency response of all three filters is shown in Fig. 12. As can be seen all demonstrate good low loss performance with excellent return loss.

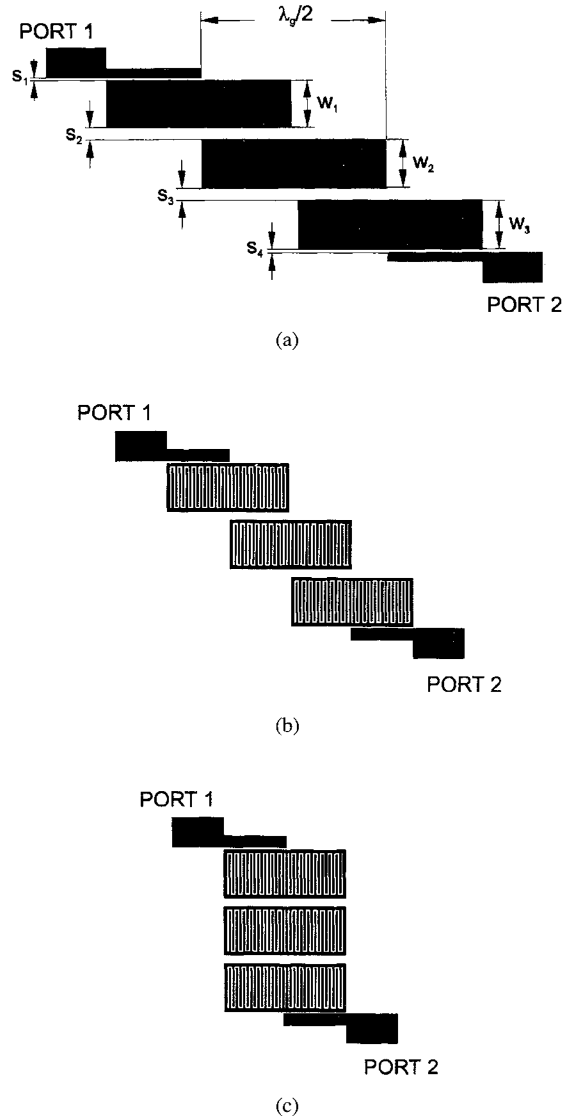


Fig. 11. (a) Edge coupled microstrip filter with conventional resonators. (b) Compact filter with slow wave line resonators. (c) Alternative filter.

V. Conclusion

A number of novel filters have been discussed which maximize the use of the area available in a microwave system more efficiently. The usual reduction in performance with this miniaturization has been offset by using high temperature superconductors. Delay line filters offer not only a miniaturization but also new capabilities not available with conventional materials. The lumped element and slow wave structures offer the microwave designer new structures which could not be effectively used previously for high frequency filters because of the large intrinsic loss associated with the structures. Some structures for these devices have been discussed but a great many new geometries have yet to be investigated. Many of these new filters have yet to be demonstrated in subsystem level applications. The application of these techniques for subsystem and system level applications not only makes the microwave section smaller but also reduces the cooling effort required. This may in fact contribute more significantly to miniature systems than the filters themselves.

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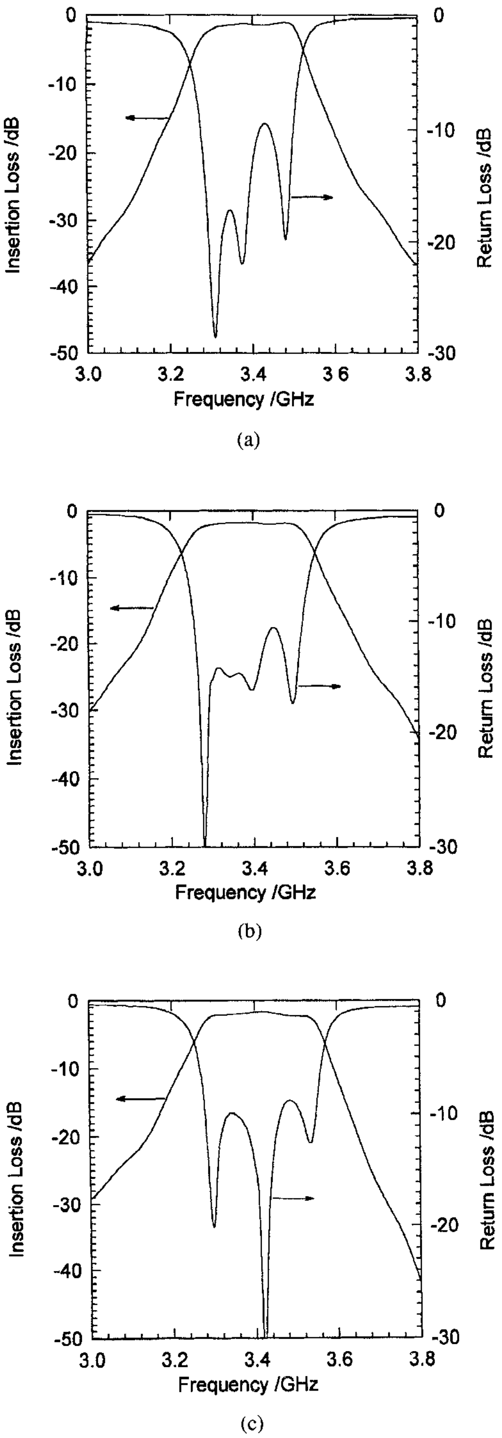

Fig. 12. Measured frequency responses for the microstrip filters shown in Fig. 11. (a) Conventional filter. (b) Compact filter. (c) In-line compact filter.

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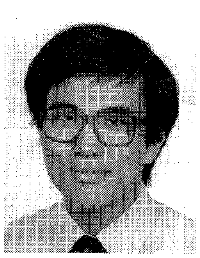

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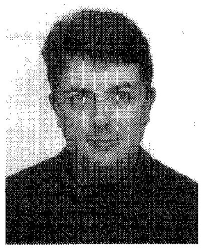

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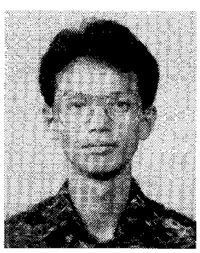

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