The Application of the FDTD Method to Millimeter-Wave Filter Circuits Including the Design and Analysis of a Compact Coplanar Strip Filter for THz Frequencies

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ABSTRACT

The finite difference time domain (FDTD) method is applied to the analysis of microwave, n~illimcter-wave and sub~~~illil~~cter-wave filter circuits. In each case, the validity of this method is confirmed by comparison with measured data. in addition, the FDTD calculations are used to design a new ultra-thin coplanar-strip filter for feeding a THz planar-antenna mixer. In this instance, the FDTD analysis is confirmed by microwave scale model measurements and by simulations performed with Hewlett Packard's Microwave Design System (MDS).

SUMMARY

Filters play an important role in the successful operation of millimeter- and submillimeter-wave mixers and frequency multipliers. Many simple filters can be designed and/or analyzed with transmission line models or lumped element prototypes (e.g. [1]). However, occasionally it is necessary to achieve a larger bandwidth of operation and/or a greater level of stopband rejection which often involves the use of more complicated filter geometries which have no simple analytic solutions. The relative simplicity and flexibility of the finite difference time domain (FDTD) method make it a particularly attractive tool for the analysis of these more complex circuits.

A. Hammerhead Filter for Microwave and Millimeter-Wave Mixers

The microstrip hammerhead filter has been an attractive candidate for use in wide stop-band mixer and frequency multiplier circuits since its introduction many years ago in [2]. However, the absence of an accurate lumped element equivalent circuit has hindered its widespread use. The FDTD analysis is an ideal tool for the design and optimization of this and similar circuit elements as a single computational run will allow the filter response to be predicted over an arbitrarily large operating frequency range.

The validity and accuracy of the FDTD technique at microwave frequencies has been investigated and verified using the hammerhead filter arrangement which appears in Fig. 1. The circuit is implemented as microstrip on fused quartz in a shielded enclosure which is sized to prevent waveguide mode propagation in the stop-band of interest. Dimensions and section lengths are given in the figure. This filter is used in a 25x scale model of a subharmonically pumped mixer [3] ant] is intended to pass the intermediate frequency (IF) mixer product below 300 MHz, while rejecting both the local oscillator (LO) signal at 4.25 GHz and the RF signal at 8.5 ± 0.3 GHz. The filter circuit was designed by cut-and-paste techniques using a Hewlett Packard 8510 vector network analyzer. The FDTD simulation was then performed on the structure to obtain the transmission characteristics shown in Fig. 2. The computation agrees well with the measurements. Indeed, several key characteristics are predicted in the calculations: the passband ripple pattern, the rapid roll-off slope, and the sharp resonances in the stopband around 8 GHz (which were thought at first to be due to imperfections in the coax-to-microstrip launchers on the filter test mount). It should be noted that the hammerhead filter structure has been anal yzed with the FDTD method before [4, 5]; however, due to the availability of a more powerful computing platform, we were able to model filters of a larger size more accurately here. With established confidence in the FDTD method, it was then possible to perform an extensive tolerance analysis which was essential for scaling the filter to higher frequencies.

The FDTD method also was used to model and optimize a similar hammerhead filter designed for use in an actual millimeter-wave subharmonic mixer with an operating frequency of 216 GHz [4]. In this case, the filter passes the IF from 1 to 20 GHz while rejecting both the 1.0 at 108 GHz and the RF at 216 ± 20 GHz. The configuration and dimensions of the filter are shown in Fig. 1. Unfortunately, the available laboratory sources allowed for measurement of this filter only in two narrow bands, 75-90 GHz and 270-290 GHz. Nevertheless, in Fig. 3 the computed response agrees well with the available measured data, especially in the region of the rapid roll-off in transmission. The FDTD analysis was also used to determine the hammerhead filter reference plane location for presenting the desired reactive impedance a fixed distance from the geometric edge of the filter.

B.   Compact Coplanar-Strip Filter for THz Applications

in applications involving transmission or detection with planar antenna structures it is often desirable to use a simple balanced-line structure for feeding the antenna element. Coplanar strip transmission line (twin-lead fabricated on a dielectric half space) is an ideal medium for feeding a wide range of two terminal antennas. For applications where more than one frequency will be present at the antenna terminals or where resistive or reactive matching is important it may be necessary to incorporate distributed filter elements with the feed line. Unfortunately the limited realizable impedance range associated with twin lead makes standard high-low impedance filters difficult to implement. in cases where the size of the feed line may be an issue (e. g. [6]) it is helpful to have a filter design with minimal projected area. Using the FDTD analysis in conjunction with scale model measurements we have designed a distributed line band-reject filter with extremely narrow cross section for applications at frequencies where the realizable thickness of the deposited metallic conductors contributes significantly to the filter characteristics.

The basic filter structure is shown in Fig. 4 and consists of quarter-wave high and low impedance sections which are contained within the confines of the 200Ω coplanar strips fabricated on a thick fused quartz substrate. The smallest proposed dimension is the 1 μ gap of the low impedance sections which gives approximately 2:1 impedance change. The filter is intended to serve a signal band-reject/intermediate frequency-pass function for use in a 2.5 THz mixer. The thickness of the conducting lines is a significant portion of their width so as to minimize skin effect losses for the IF. The FDTD technique was used to analyze the effects of the metal line thickness, width and air-gap as well as to determine the radiative losses, the characteristic line impedance and the open-circuit reference plane. The analysis was verified using a 1680X scale model of the proposed 2.5 THz filter with thick brass sheet to form the metallic lines and stycast $\varepsilon_r = 3.8$ to model the quartz substrate. Unfortunately, the lack of a good broadband balun to transition from the 50Ω coaxial test cable of an HP8510 to the $\sim 200\Omega$ coplanar strip line necessitated that the filter response be measured over several narrow bands between 1 and 2.5 GHz. In Fig. 5 the FDTD calculations arc compared with the available measurements. Although the agreement is not as good as in the hammerhead filter case, the similarity is encouraging as it appears that the measured rejection band and the rising slope after it are fairly close to the calculated results. We are confident that with an improved, broader band balun the agreement between the computed and measured results would be much better.

The coplanar strip filter was also simulated using HP's Microwave Design System (MDS) program. In Fig. 6, the FDTD and MDS calculations are compared. With only a small shift in the frequency response and a small difference in the magnitude, they both predict the same ripple

pattern in the pass regions as well as the same cutoff frequency. The growing discrepancy in magnitude in the region beyond 4 THz is largely due to radiation loss present in the FDTD calculations but not present in the MDS simulation. This example shows that, at least for this simple filter, both the FDTD method and MDS can be used to provide useful design information about the coplanar strip filter.

in this paper, the FDTD method is used in the design and analysis of filters in the microwave, millimeter-wave and submillimeter-wave regions. In each case, the FDTD method is shown to provide fairly accurate characterizations. HP's MDS program is also used to characterize the 2.5 THz coplanar strip filter where the results agree well with the 1"1)"1'1) calculations, if radiation loss is ignored. The FDTD technique clearly plays a useful role in the design and analysis of transmission line filter structures for applications at microwave, millimeter and submillimeter wavelengths. Its unique ability to determine complete S parameter response over an arbitrarily large frequency range in a single computation offer an advantage for this type of broadband circuit application. The agreement so far obtained between the FDTD method and experimental measurement is excellent and the method is now being extended to include waveguide structures and nonlinear device analysis.

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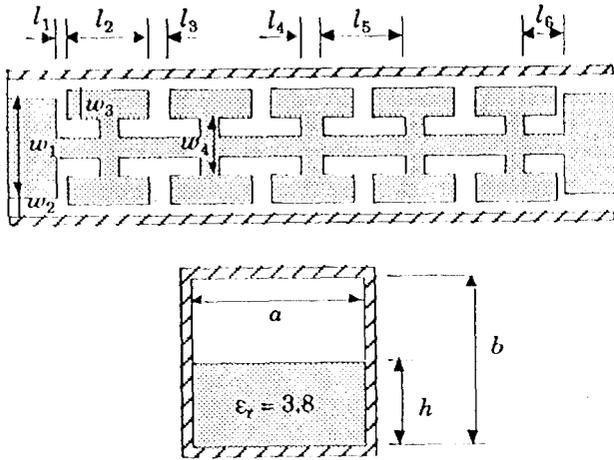
Fig. 1 Hammerhead filter arrangement (not to scale). Dimensions (in mm) for 8 GHz filter are: $l_1 = 1.321$, $l_2 = 11.43$, $l_3 = 1.321$, $l_4 = 1.321$, $l_5 = 11.43$, $l_6 = 6.375$, $w_1 = 4.928$, $w_2 = 1.473$, $w_3 = 2.108$, $w_4 = 2.286$, $a = 7.874$, $b = 7.62$, h = 3.81. Dimensions (in pm) for 216 GHz filter are: $l_1 = 52$, $l_2 = 450$, $l_3 = 52$, $l_4 = 52$, $l_5 = 450$, $l_6 = 251$, $w_1 = 194$, $W_2 = 68$, $w_3 = 82$, $w_4 = 90$, $a = 330$, $b = 330$, h = 165.
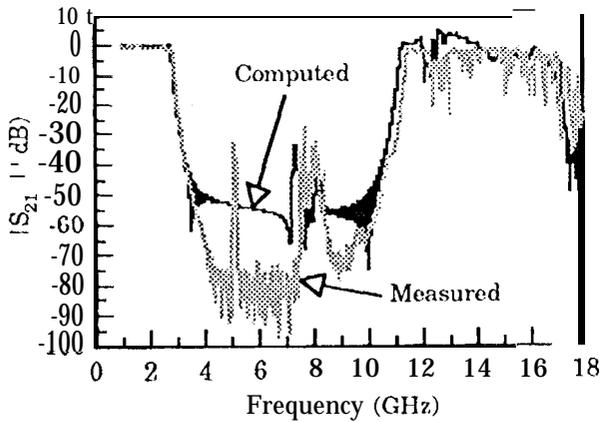
Fig. 2 FDTD and measured transmission response for 8 GHz hammerhead filter.
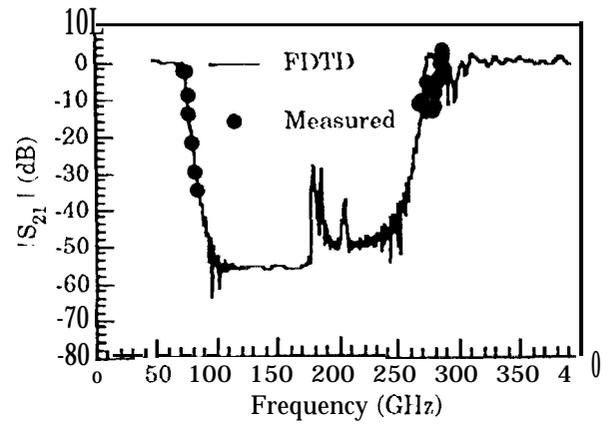
Fig. 3 FDTD and measured transmission response for 216 GHz hammerhead filter.
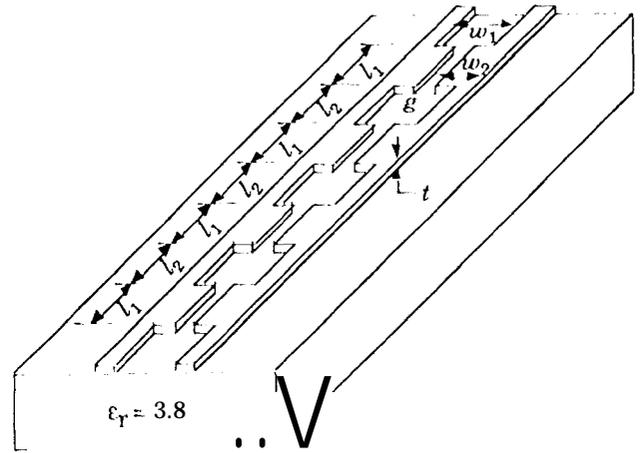
Fig. 4 Coplanar strip filter (not to scale). Dimensions in μm are: $l_1 = 22.1$, $l_2 = 18.7$, $w_1 = 3.0$, $w_2 = 2.0$, g = 1.0, $t = 1.0$.
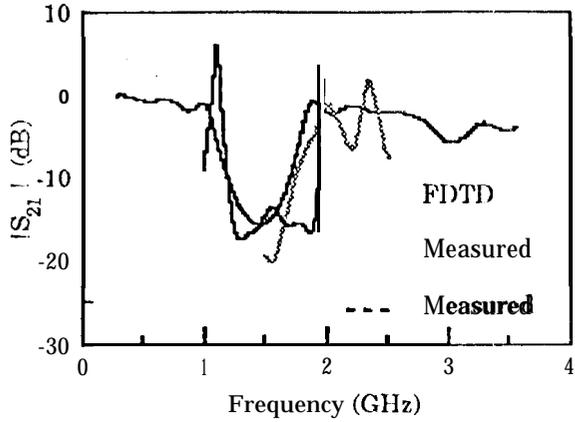
Fig. 5 FDTD and measured transmission responses for 168ox scale model of coplanar strip filter of Fig. 4. Filter was measured in 2 bands.
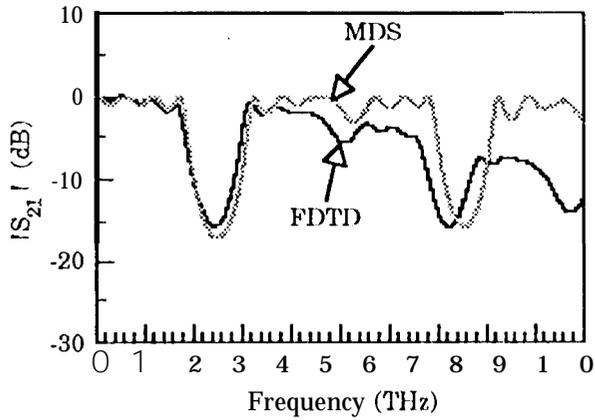

Fig. 6 FDTD and MDS transmission responses for coplanar strip filter.