Plasma-Dielectric Sandwich Structure Used as a Tunable Bandpass Microwave Filter

GWO-CHUNG TAI, CHUN HSIUNG CHEN, AND YEAN-WOEI KIANG

Abstract —A plasma-dielectric sandwich structure used as a tunable bandpass filter in a microwave spectrum is investigated in detail. The unique characteristics of this filter are that the center frequency of its passband and its bandwidth can be tuned electrically by varying the electron density of the plasma, which in turn can be adjusted by a voltage applied across the plasma electrodes. First, the principle in establishing the filtering effect is briefly discussed physically with an aim of suggesting a practical structure for theoretical analysis. A conventional multilayer theory is then employed to analyze this plasma-dielectric structure, and an optimization technique called the simplex method is used to find the center frequency. Both cases of having the TE_{10} dominant mode in a rectangular waveguide and the TEM mode in an unbounded structure are studied. Finally, included are the computed results for characterizing the filter such as reflection coefficients, center frequencies, bandwidths, quality factors, and lossy effects, etc.

I. Introduction

Tunable bandpass microwave filters are indispensable components in an electronic system. This study supplies useful results to a new structure, as suggested in a recent work [1].

In an analysis of wave propagation in an inhomogeneous slab, a complete transmission window is observed to associate with a dielectric profile, with several positive–negative permittivity variations [2], [3]. In fact, any sandwich structure with a positive permittivity slab separating two negative permittivity layers is found capable of producing such a complete transmission, a phenomenon that is due to a leaky resonance plus partial tunneling established within the structure [2]. This leaky resonance phenomenon could be utilized to implement new electronic devices in a communication system. For instance, a tunable filter, an on–off switch, or a modulating device, etc., could be constructed in a microwave domain by incorporating a suitable control on the voltage applied across the new device. Besides, the communications blocking due to the plasma sheath around a space vehicle could also be overcome by introducing an additional negative permittivity plasma layer inside the vehicle so as to create a new transmission window purposely.

The objectives of this study are twofold: one is to show that the use of the plasma-dielectric structure as a tunable microwave filter is feasible, and the other is to provide the necessary information in designing the new filter.

II. Filter Structure and Basic Principle

A tunable bandpass microwave filter which has the multilayer plasma-dielectric sandwich structure (Fig. 1) is investigated. The relative permittivities of plasma and dielectric are $\epsilon_p(<0)$ and $\epsilon_d(>0)$, respectively, which are assumed to be isotropic and homogeneous. All regions are assumed to have the same permeability μ_0. In the first part of this study, the plasma is described by a cold and lossless model [4] so that

$$\epsilon_p = 1-(\omega_p/\omega)^2 \tag{1}$$

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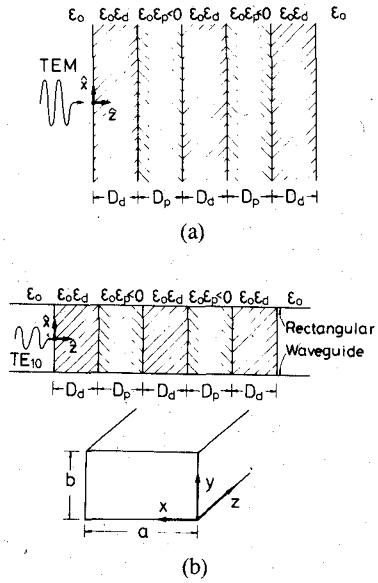

Fig. 1. Geometry of plasma-dielectric sandwich filter. All regions are isotropic as well as homogeneous and have the same permeability μ_0. (a) TEM wave in unbounded structure. (b) TE_{10} dominant mode in rectangular waveguide.

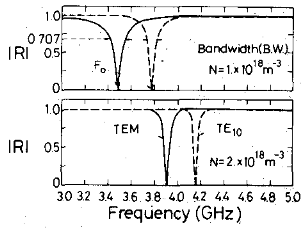

Fig. 2. Typical response curves (reflection coefficient $|R|$ versus frequency) to depict variations of center frequency and bandwidth for various electron densities N ($\epsilon_d = 5.24$, $D_d = 1.0$ cm, $D_p = 0.8$ cm).

where

$$\omega_p^2 = Ne^2/m\epsilon_0. \tag{2}$$

In the above equations, ω_p and ω are the plasma and wave frequencies, while N, e, and m are the density, charge, and mass of the free electron in plasma, respectively. This filter should be operated in the spectrum for which the plasma frequency is greater than the wave frequency so that the plasma permittivity may be made negative.

The basic idea for establishing the filtering characteristics (see Fig. 2) can be described briefly. For most frequencies, the negative permittivity plasma slabs may serve as imperfect reflectors (or barriers) which exhibit large reflection (reflection coefficient $|R| \approx 1$) to the incident wave. However, in some frequency bands, the structure may act like a bandpass window which allows the incident wave to pass through, even with no reflection. More precisely, a complete transmission window ($|R| = 0$) is found to exist at the center frequency F_0 of the passband due to the mechanism of leaky resonance [2], plus partial tunneling. In particular, associated with this complete transmission phenomenon is a large field (or energy) established within the central dielectric slab (see Fig. 3).

In this study, the formulation of using a multilayer theory and a backward propagation matrix [5] is employed to attack the reflection coefficient R of the proposed plasma-dielectric structure. The reflection coefficient can be related to various quanti-

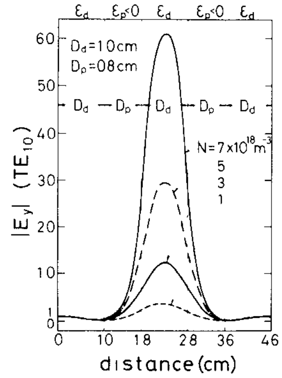

Fig 3 Electric-field distribution within plasma-dielectric structure at complete transmission frequency with electron density N as parameters ($\epsilon_d = 5.24$).

ties such as the center frequency of the passband, bandwidth of the filter, and wave field distribution, etc. An optimization technique called the simplex method [6] is adopted in searching the center frequency of the passband at which the reflection coefficient R is zero. Note that, since $\epsilon_p < 0$ (i.e., $\omega < \omega_p$), the square root in the propagation constant $K_p = \omega\sqrt{\mu_o \epsilon_o \epsilon_p}$ should be chosen to be negative imaginary so that an evanescent wave can be generated in the plasma regions (we adopt the $\exp(j\omega t)$ convention).

III. Numerical Results and Discussion

Typical response curves, depicting reflection coefficient versus frequency, to characterize the transmission properties of the plasma-dielectric filter are shown in Fig. 2 for illustration. The bandwidth $B.W.$ will be defined as the frequency band for which half of the incident wave power is transmitted. As indicated, the center frequency F_0 is just the particular frequency at which complete transmission takes place.

The bandwidth characteristics of the plasma-dielectric filter can also be described by a quality factor Q, as defined by

$$Q = \omega_0 U/P. \tag{3}$$

Here, ω_0 is the center frequency ($2\pi F_0$), i.e., the complete transmission frequency, of the filter. By lossless assumption and by symmetry of the structure, the leaked power P should be twice that of the transmitted power through the filter. And the energy U stored in the structure may be computed from an integration of the energy density [7]

$$u = \frac{1}{4}|E|^2 \frac{\partial}{\partial\omega}(\omega\epsilon_0\epsilon) + \frac{1}{4}\mu_0|H|^2 \tag{4}$$

where E and H are the electric and magnetic fields of the filter at the frequency of complete transmission. As usual, the fractional bandwidth $B.W./F_0$ of the plasma-dielectric filter may be related to the quality factor Q by the well-known formula

$$Q \approx F_0/B.W. \tag{5}$$

As a verification of this interpretation, both Q and $F_0/B.W.$ are calculated separately and tabulated in Table I, which shows good agreement in both computations.

Shown in Fig. 3 are the spatial distributions of electric fields (E_y) for various cases at resonance (complete transmission). As revealed, a very large field (or energy) does distribute in the central dielectric, which again gives evidence of both leaky resonance and partial tunneling.

Depicted in Figs. 4–7 are some typical curves to show the variations of center frequency F_0 and bandwidth $B.W.$ versus electron density N. The curves for TEM and TE$_{10}$ cases are

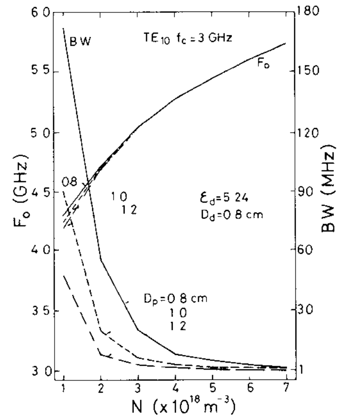

Fig. 4. Center frequency F_0 and bandwidth $B.W.$ versus electron density N with plasma thickness D_p as parameters

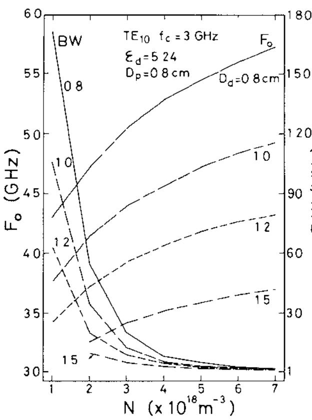

Fig. 5 Center frequency F_0 and bandwidth $B.W.$ versus electron density N with dielectric thickness D_d as parameters.

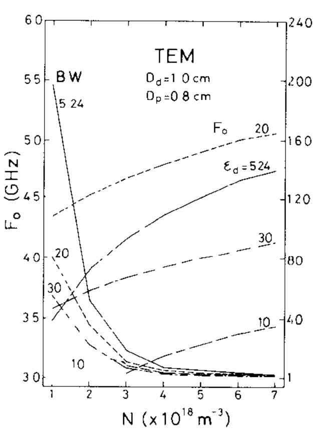

Fig. 6. Effect of dielectric constant ϵ_d on center frequency F_0 and bandwidth $B.W.$

similar in appearance and tendency, except that their center frequencies and bandwidths are different, hence only the TE$_{10}$ or TEM case is presented in each illustration. In this study, the cutoff frequency of the TE$_{10}$ mode is taken as 3 GHz.

Let us consider the results in Fig. 4 where D_d is specified. If one increases the electron density, the center frequencies associated with different D_p will finally merge into a single curve as shown in the figure. The center frequency F_0 is actually predetermined by the thickness of dielectric slab D_d. On the other hand, the wider the D_p is, the narrower the bandwidth is observed. To explain this, one must notice that the reflecting action of a negative permittivity plasma slab increases as D_p or N is

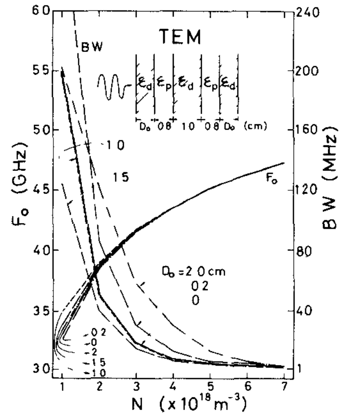

Fig. 7. Effect of outer dielectric thickness D_o ($\epsilon_d = 5.24$).

TABLE I
SEPARATE COMPUTATIONS TO SHOW THE AGREEMENT OF $F_0/B.W.$ AND Q-FACTOR

	$N(\times 10^{18}m^{-3})$	1	2	3	4	5	6
TEM	F_o/B.W.	17.76	76.60	242.0	635.5	1477	3132
	Q	18.86	76.22	245.0	633.9	1476	3140
TE_{10}	F_o/B.W.	35.12	126.5	370.0	930.7	2106	4363
	Q	35.88	125.0	366.2	926.2	2100	4375

Note: Results for both TEM and TE_{10} cases are presented for the filter with $D_d = 1$ cm, $D_p = 0.8$ cm, and $\epsilon_d = 5.24$

increased. Thus more energy will be stored within the central dielectric slab to enhance the corresponding Q-factor and to reduce the bandwidth as D_p or N is increased.

Illustrated in Fig. 7 are the curves to demonstrate the effect of varying the thickness D_o of the outer dielectric slabs. The center frequency is indeed determined by the thickness of the central dielectric slab by comparing the curve for $D_o = 0$ with those for other D_o's. As shown, the variation of D_o has little effect on the center frequency. On the contrary, the magnitude of D_o still has considerable influence on the bandwidth, although its effect is not regular.

An actual plasma always exhibits losses whose relative dielectric constant may be expressed as [7]

$$\epsilon_p = \epsilon_p' - j\epsilon_p'' \tag{6}$$

where

$$\epsilon_p' = 1 - \frac{\omega_p^2/\omega^2}{1+(\nu/\omega)^2} \tag{7}$$

$$\epsilon_p'' = \frac{(\omega_p/\omega)^2(\nu/\omega)}{1+(\nu/\omega)^2}. \tag{8}$$

Here, ϵ_p'' accounts for losses in plasma and ν is the collisional frequency between electrons and molecules or ions. Fig. 8 presents curves (for the TE_{10} case) to characterize the lossy effect with ν/ω as a parameter. The complete transmission window is found to disappear when a loss is introduced, and the reflection becomes pronounced as ν/ω becomes large.

IV. CONCLUSIONS

A phenomenon of having complete transmission in some frequencies and large reflection in other frequencies has been utilized

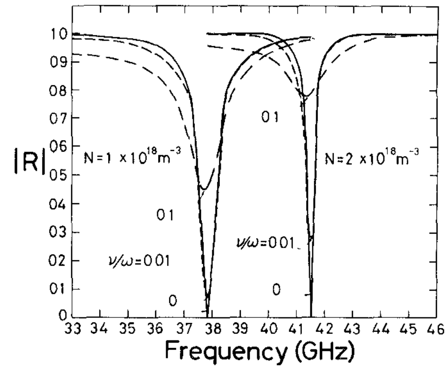

Fig. 8. Illustration of lossy effect for $D_d = 1.0$ cm, $D_p = 0.8$ cm, and $\epsilon_d = 5.24$ (TE_{10} case).

to implement a new tunable bandpass filter in a microwave regime. Many useful results for specifying the filter performance have been presented and investigated in detail.

The new filter is analyzed based on a simple model of cold plasma. Hence, an experimental work is definitely needed as a future study in complementing the simplified theory developed in this study.

The leaky resonance phenomenon may be useful in constructing other new devices for special purposes, e.g., as an on–off switch or a modulating device. The characteristics of the plasma-dielectric structure may also be tuned externally by applying a steady magnetic field across the plasma.

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Dielectric Waveguide Corner and Power Divider with a Metallic Reflector

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Abstract —**The right-angle corner and T- and Y-junction-type power dividers with the metallic reflector are experimentally investigated which are useful for dielectric waveguide millimeter-wave integrated circuits.**

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