V. Conclusion

In this paper, the authors have demonstrated successful modeling of strip polarizers in waveguide using a 2.5-D MoM analysis tool. The test cases considered showed good agreement between measurement and simulations, including phase information. Good polarization isolation was achieved with the close-spaced geometries with 20–25 dB of attenuation between modes, and negligible pass-mode attenuation. The accurate prediction of the inductive behavior of these devices could enable the design of waveguide filters and matching networks using cascaded arrays of passive structures. The approach used is applicable to arbitrary metallizations and cascaded structures enclosed within rectangular or square waveguide.

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Study of a Combined Millimeter-Wave Resonator

M. A. Shapiro and S. N. Vlasov

***Abstract*—We present a theoretical investigation and measurements of a multielement open resonator composed of corrugated waveguides and plane semitransparent reflectors. A periodic-transmission-line model is used to analyze the transverse mode structure and the diffraction Q-factor of the proposed resonator. The setup containing the resonator (equipped with Bragg reflectors), mode converters, and an elliptical mirror is employed for measurements in Ka-band. Two- and three-waveguide-section resonators have been studied. The proposed resonators demonstrate good mode selectivity that permits one to utilize them in high-power millimeter-wave sources.**

***Index Terms*— Millimeter-wave resonators, transmission-line resonators.**

I. Introduction

In high-power millimeter-wave generators based on relativistic electron beams, extended oversized resonators are used to operate at the high current. To accomplish single-frequency and single-mode operation of these sources, the resonators are bound to be selective. The resonator selectivity means that diffraction losses of the operating mode are required to be less than diffraction losses of spurious modes whose transverse structure and frequency are different from those for the operating mode.

The proposed resonator achieves frequency and modal selectivity by containing several oversized waveguide sections and mirrors set coaxially with gaps [Fig. 1(a)]. Sections of an axially symmetric corrugated waveguide can be used in this resonator to provide extremely low Ohmic losses and diffraction losses for the operating mode. The period of corrugation of the waveguide wall is essentially less than the wavelength λ and the corrugation depth is a quarter wavelength $\lambda/4$ [1]–[4].

The waveguide wall is actually an impedance wall. An electromagnetic field in such an impedance-wall waveguide can be represented by a superposition of the linearly polarized modes HE_{11}, HE_{12}, HE_{13}, and so on. For the HE_{11} mode transferred through a gap between the waveguide sections, diffraction losses can be quite small since the HE_{11} mode comprises 98% of the TEM_{00} free-space Gaussian beam optimized for its waist. However, diffraction losses at the gap can be reduced considerably if we apply the mixture of the HE_{11} and HE_{12} modes composing the TEM_{00} beam precisely. The required mixture of modes can be maintained in the combined resonator if the resonator length is equal to integer multiples of the beat length between the HE_{11} and HE_{12} modes in the waveguide. Thus, the lowest linearly polarized mode of a combined resonator is represented by the TEM_{00} mode in the cross section of the gap and the HE_{11}/HE_{12}-mode mixture in the waveguide sections.

Frequency drift and a change in the transverse index lead to an increase in diffraction losses at the gaps and, as a result, to a reduction

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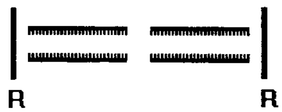
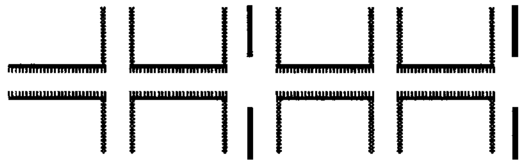


(a)



(b)

Fig. 1. Combined systems (a) Resonator. (b) Transmission line.

of the Q-factor. Therefore, these diffraction losses provide frequency and transverse-mode index selectivity.

II. Theoretical Analysis

We calculate only the lowest mode, which has minimum diffraction losses. To find the field distribution, propagation constant, and losses of this mode, we use the equivalence of the resonator mode at the resonance frequency to the mode of a transmission line containing an infinite periodic sequence of waveguide sections and diaphragms set coaxially [Fig. 1(b)]. The inner diameter of diaphragms is equal to the mirror diameter in the resonator [Fig. 1(a)]. The transparency coefficient of the diaphragms is equal to the reflection coefficient R of the mirrors in the resonator. We account for the open ends of the resonator waveguides in the equivalent transmission-line model with fully absorbing medium diaphragms [Fig. 1(b)].

The eigenmodes of a combined transmission line [Fig. 1(b)] can be calculated by solving an eigenvalue problem for the integral equation with respect to the linearly polarized component of electric field E

$$E(r,\, z+D) = \hat{G}E(r,\, z) = K_0 E(r,\, z) \tag{1}$$

where r and z are radial and longitudinal coordinates, D is the transmission-line period (a distance between diaphragms), and K_0 is the one-period transmission efficiency, which is an eigenvalue of the operator $\hat{G}$ of one-period propagation. The eigenvalue K_0 is determined numerically through repeated application of the operator $\hat{G}$ to the electric field (i.e., $E(r,\, z+D) = \hat{G}E(r,\, z)$; $E(r,\, z+2D) = \hat{G}E(r,\, z+D)$; etc.) until the ratio $E(r,\, z+nD)/E(r,\, z+(n-1)D)$ approaches a constant, which is evidently K_0. The operator $\hat{G}$ itself related to the propagation in one period of the line is a multiplication of two operators: $\hat{G} = \hat{G}_{\rm gap}\hat{G}_w$.

The operator $\hat{G}_{\rm gap}$ corresponding to propagation across the gap between waveguides (or between a waveguide and a diaphragm) is represented by [5]

$$\hat{G}_{\rm gap}E(r) = i\frac{k}{L_{\rm gap}}\int_0^a E(r')J_0\left(\frac{krr'}{L_{\rm gap}}\right)\exp\left(-i\frac{k(r^2+r'^2)}{2L_{\rm gap}}\right)r'dr' \tag{2}$$

where $L_{\rm gap}$ is the length of the gap, a is the waveguide (diaphragm) radius, k is the free-space wavenumber, and J_0 is the zeroth-order Bessel function.

The operator $\hat{G}_w$ corresponding to propagation in the corrugated waveguide is determined by assuming a composition of HE_{1n} modes in the waveguide and by taking into account the boundary condition $E = 0$ at the corrugated waveguide wall within an impedance approach [4]:

$$\hat{G}_w E(r) = \sum_n C_n J_0\left(\frac{\mu_n}{a}r\right)\exp\left(i\frac{\mu_n^2 D_w}{2ka^2}\right) \tag{3}$$

where D_w is a waveguide length and μ_n is the nth zero of the Bessel function J_0. The coefficients C_n are determined by a mode expansion of the electric field $E(r)$ at the open end of the waveguide. The diaphragm is considered as a waveguide of a zero length.

An eigenfunction $E(r,\, z)$ and an eigenvalue K_0 of (1) are then determined using the above-described iteration procedure. The transmission coefficient K_0 of the equivalent line, then permits one to find diffraction losses in the resonator $\delta_{\rm dif} = 1 - K_0^2$ and the Q-factor $Q = kL_{\rm res}/\delta_{\rm dif}$, where $L_{\rm res}$ is the resonator length.

Subsequent calculations confirm the fact that the resonator mode has its minimum diffraction losses for the given length of gaps if $L_{\rm res}$ is an integer multiple of the beat length between the HE_{11} and HE_{12} modes [6], [7]

$$\Lambda_{12} = \frac{4\pi ka^2}{\mu_2^2 - \mu_1^2} = 0.51ka^2.$$

III. Set-up for Resonator Test

At the 28–38-GHz frequency range, we study a combined resonator composed of one or more sections of corrugated, axially symmetrical waveguide (1 in Fig. 2), where each waveguide section is 120-mm-long and the inner diameter of the waveguide is 40 mm. The period of rectangular corrugation of the waveguide wall is 2 mm, and the corrugation depth is 2 mm. We use Bragg reflectors (2 in Fig. 2) that are composed of quarter-wave quartz plates (dielectric permittivity $\varepsilon = 3.75$) set in the 40-mm-diameter waveguide. The quartz-plate thickness is 1.2 mm and the distance between plates is 2.3 mm.

The resonator is excited by a horn (4 in Fig. 2), which converts the TE_{11} mode of a circular waveguide into the TEM_{00} Gaussian beam. The circular horn has a parabolic taper [8], [9] with a length of 111 mm and aperture diameter of 114 mm. The ellipsoidal mirror (3) has curvature radii of 340 mm in the plane of Fig. 2 and 170 mm in the perpendicular plane, and forms a collimated Gaussian beam at the resonator position (100–150 mm from the center of the mirror). Adiabatic waveguide tapers (5) are used to convert the TE_{10} mode of a rectangular waveguide into the TE_{11} mode of a circular waveguide.

Directional couplers (6) are used for measurement of the efficiency of transmission through the resonator $T = (U_{\rm trans}/U_{\rm inc})^2$, which depends on frequency and on the efficiency of transmission K_0 between the resonator mirrors:

$$T = \frac{(1-R^2)(1-K_0^4)}{(1-K_0^2)^2 + 4K_0^2\sin^2 {\rm kL_{res}}} \tag{4}$$

where R is the reflection coefficient of the Bragg reflector. The measurement of dependence of T on frequency permits one to find efficiency K_0, and therefore, the Q-factor.

IV. Results of Measurement and Comparison to Calculations

Fig. 3(a) and (b) shows the results of measurement and calculations of the Q-factor of two resonators: a) consisting of two waveguide sections with $L_{\rm gap} = 24$ mm between them and a mirror-waveguide separation distance of $L_m = 12$ mm; b) consisting of three waveguide sections with $L_{\rm gap} = 19$ mm and $L_m = 17.5$ mm. These results

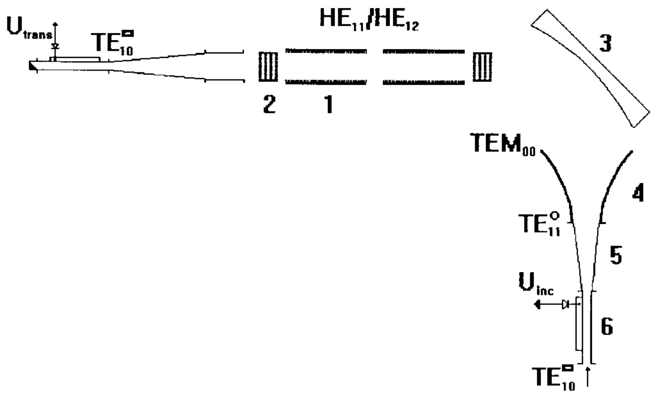


Fig. 2. Set-up schematic: 1) corrugated waveguide section; 2) Bragg reflector; 3) elliptical mirror; 4) mode converter; 5) waveguide taper; 6) directional coupler.

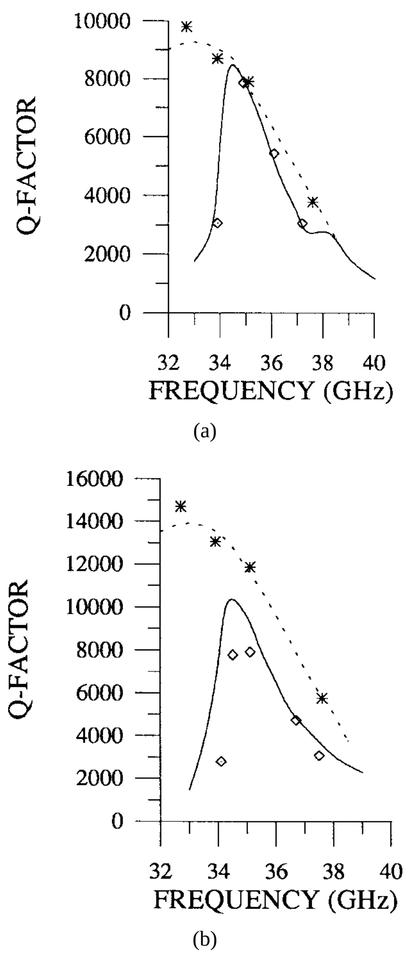


Fig. 3. Results of calculation (solid and dashed lines) and measurement (◊ and *) of the combined resonators, containing two (a) or three (b) waveguide sections: — and ◊ gaps included; — and * no gaps.

correspond to the case of four quartz plates composing the Bragg reflectors.

For the calculations we assume the Bragg reflector has its characteristic field length of 3.5 mm, which is included in the L_m parameter. This field length is determined by analyzing the Fabry–Perot resonator with Bragg reflectors.

To demonstrate the selectivity of the resonator, Fig. 3(a) and (b) includes the results of measurement and calculation of the resonators containing the same waveguide sections but no gaps. It is seen that the resonator losses are frequency-dependent even if no gaps exist. This reflects the fact that we operate at the high-frequency edge of the bandgap of Bragg reflectors. The gaps lead to increasing of losses (decreasing of the Q-factor) at low frequencies where the gap diffraction is stronger. As a result, both the gaps and Bragg reflectors create a narrow-band dispersion of Q-factor and thus make the resonator frequency selective.

The tested two-section and three-section resonators have the same 0.17 ratio of the total gap length to the resonator length and thus about the same dependence of Q-factor on frequency, which is responsible for selectivity. However, the mode spectrum in the two-section resonator is rarer than that in the three-section resonator. So, in the two-section resonator, there is a single mode whose Q-factor is 50% higher than for the adjacent mode, whereas in the three-section resonator, a high-Q-factor single mode is not separated.

V. Conclusion

Resonators formed from sections of corrugated waveguide and plane mirrors have been investigated in Ka-band. Based on the results obtained, we propose to use the combined resonators in high-power millimeter wave generators (CARM, ubitron, and so on). Due to the resonator selectivity, the operating-mode excitation requires less start current of an electron beam than those for spurious modes. This feature results in increased single-mode power from the generator.

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