High-Performance Transitions for Overmoded Operation of Elliptical Waveguides

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***Abstract*—Overmoded elliptical waveguide systems are shown to provide considerable lower insertion loss compared with standard types using the frequency band with exclusive TE_{c11} fundamental mode propagation. The considerations for the overmoded waveguide operation are outlined. A novel transition design based on transformer steps with curved cross sections and containing means for higher order mode control is established for interfacing the oversized elliptical cross section with the standard rectangular waveguide ports. The accurate determination of the transition structure maintaining high performance demands is obtained by a suitable computer-aided-design procedure. The overmoded waveguide approach, including the transition design, is proven by computed and experimental results for a millimeter-wave design.**

***Index Terms*—Elliptical-to-rectangular waveguide transition, higher order mode suppression, low insertion-loss waveguides, mode filter, overmoded elliptical waveguide.**

I. INTRODUCTION

HIGH-CAPACITY radio relay stations generally make use of waveguide systems for low-loss interconnection of the radio equipment located at accessible areas (e.g., in operational rooms) with the antennas situated at exposed positions, e.g., on towers or hills (Fig. 1).

The particular demands on these waveguide systems are low cost (regarding components and installation), while maintaining high electrical performance, i.e., low loss and good matching properties (>30-dB return loss) within broad transmission bands. For standard operation, these waveguide systems with lengths of over 20 m have been established to consist of a waveguide run with elliptical cross section and proper transitions for interfacing the standard rectangular waveguide ports of the radio equipment and antenna feed system.

Commonly, there are corrugated [1] and smooth wall [2] elliptic waveguides, exhibiting particular bendable and twistable properties that facilitate easy handling and installation since they allow the realization of the complete waveguide run in one part—an essential advantage compared with other waveguide types. Moreover, they provide lower insertion loss than standard rectangular cross-sectional types. However, standard waveguide systems that are operated in the frequency band with exclusive fundamental mode propagation become more and more lossy at higher frequency bands (>10 GHz), resulting in decreased system margins, smaller possible hop length, and the need of larger antenna diameters or higher power level output, respectively.

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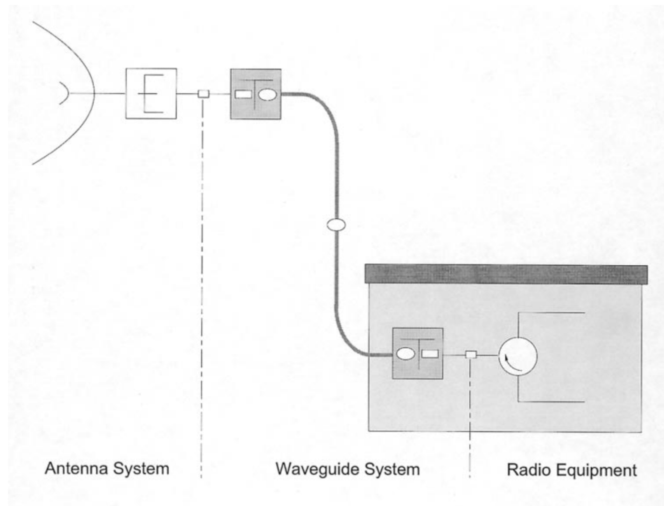

Fig. 1. Principal block diagram of a radio station.

Considerable low transmission loss can be obtained by overmoded waveguide systems, i.e., the operation of a dedicated higher order mode within the useful frequency band, while other mode types that may also propagate are suppressed to avoid any impairment on the transmission response. Solutions with circular waveguides operated with the TE_{01} mode were investigated, e.g., in [3]. The theoretical low-loss advantage of the straight sections of such a waveguide run is essentially reduced by bends and mode launchers due to the conversion of signal energy into other modes, thus requiring additional mode filters to avoid any impairment [4]. Since there will only be a petty loss improvement for a typical radio–antenna interconnection, the additional high expense of handling and installation make such solutions unattractive for radio stations.

Another overmoded waveguide approach is based on the fact that the operation of the fundamental mode within a waveguide with an oversized cross section also yields significant reduced insertion loss compared with the operation within a standard waveguide type. However, higher order modes, which may also propagate within such an oversized waveguide, have to be controlled conveniently to avoid any impairment on the transmission. This approach is well suited for elliptical waveguide types, owing to their favorable handling and installation properties, since the standard waveguide types can be applied to overmoded operation at higher frequency bands.

This paper presents the considerations for the fundamental mode operation within overmoded elliptical waveguides—in

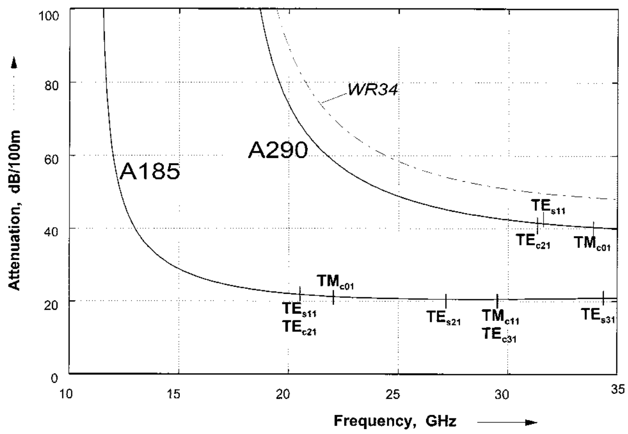

Fig. 2. Fundamental mode (TE_{c11}) attenuation of the A185 and A290 ALFORM waveguides and marked cutoff frequencies of higher order modes [the attenuation characteristic of the standard WR34 (R260) waveguide is shown for comparison (dashed line)].

particular, the design constraints for the transitions required for interfacing the oversized elliptical waveguide cross section with a standard rectangular waveguide port. In order to accommodate high performance and low-cost demands, a transition design based on a step transformer with curved cross sections has been established, facilitating easy production by computer numeric control (CNC) milling techniques. It contains suitable means for the control of higher order modes, which may be excited within the oversized waveguide, without impairment on the fundamental mode response. The design is supported by a novel mode-matching computer-aided design (CAD) providing accurate dimensioning and performance prediction. For the verification of the design method, an overmoded transition has been realized, which shows excellent coincidence of computed and experimental results. In addition, an elliptical waveguide equipped with two transitions has been measured to prove the high performance of the overmoded elliptical waveguide approach including higher order mode control.

II. Design Considerations for Overmoded Waveguides

Fig. 2 depicts the principal fundamental mode attenuation characteristics of two smooth-wall elliptical aluminum waveguides (ALFORM)—standard operation with exclusive TE_{c11} fundamental mode propagation is dedicated for the A185 to the frequency band 17.5 to 20 GHz and for the A290 to the band 24.5 to 30 GHz. (Elliptical cross section of A185 $a = 15.88$ mm, $b = 8.25$ mm, and A290 $a = 10.4$ mm, $b = 5.35$ mm). A comparison of both characteristics at the A290 standard operation band exhibits nearly half the loss (in decibels) for the A185. However, there are several higher order modes that may also propagate as the indication of their cutoff frequencies in Fig. 2 shows. Thus, the utilization of the loss advantage can only be achieved by proper higher order mode control within the overmoded waveguide system since any conversion of the fundamental mode into higher order modes will lead to an increase of insertion loss and may impair the system due to multipath propagation effects.

Hence, particular demands are imposed on the transition design for interfacing the overmoded waveguide with the dedicated standard rectangular waveguide ports, namely,

- low voltage standing wave ratio (VSWR) (typically 1 : 1.04, return loss >34 dB);
- low insertion loss—no increase by means for higher order mode suppression;
- higher order mode control including: 1) avoidance of their excitation within the transition and 2) means for suppression of the small higher order mode signal portions that may occur by weak mode conversions within the overall waveguide system;
- low-cost production by CNC milling techniques.

III. General Transition Design

Several different aspects have to be considered carefully to cope with the above requirements. Transitions based on smooth wall taper functions, as presented in [1], [5], may provide high performance. However, the production expense is rather high due to the application of several manufacturing processes, e.g., electroforming, milling, and soldering.

For that reason, a very compact transition design with transformer steps is preferred. It can be realized by machining from a transverse cutting plane as well as from the flanges by state-of-the-art CNC milling techniques, thus facilitating overall low-cost production. However, the design approach for this general transition configuration has to consider milling radii within the transformer cross sections to cope with the high-performance demand. To essentially reduce the development expense and time for such transitions, a novel mode-matching CAD tool has been established that allows accurate analysis and optimization of the structure.

A. CAD Method for Transition Design

The CAD is based on the mode-matching method (MMM) combined with a gradient optimization strategy [6]–[8]. The MMM allows a full-wave analysis of the electromagnetic fields generated by a waveguide step and is only restricted to the accuracy of the calculation of eigenmode interaction at the discontinuity. Changing the relevant mechanical parameters allows, for example, the improvement of the return loss or the reduction of higher order mode coupling by applying a suitable optimization algorithm.

The use of the MMM requires the computation of the complete set of eigenmodes of all waveguide sections of the transition and of the connected waveguides. Therefore, the eigenmodes of elliptical waveguides and rectangular waveguides with rounded corners must be determined first. The eigenmodes of curved cross sections can be computed with a boundary contour method (BCM) [9], [10]. Each eigenmode is expanded into a series of the eigensolutions of the circular wave equation (products of Bessel functions and trigonometric functions), represented here by the axial components of the generating electric and magnetic vector components

$$F_z = \sum_{p=0}^{\infty} \left[A_p \cos(p\varphi) + B_p \sin(p\varphi)\right] J_p(Kr) e^{-\gamma z} \qquad (1)$$

$$A_z = \sum_{p=0}^{\infty} \left[C_p \cos(p\varphi) + D_p \sin(p\varphi)\right] J_p(Kr) e^{-\gamma z}. \quad (2)$$

The expansion coefficients A_p, B_p, C_p, and D_p depend on the curvature of the cross section. K is the radial wavenumber and γ the complex propagation constant. The electric field is defined by

$$\vec{E} = -\text{curl}\ (0, 0, F_z)^{\mathrm{T}} + \frac{1}{j\omega\varepsilon}\ \text{curl curl}\ (0, 0, A_z)^{\mathrm{T}}. \quad (3)$$

Solving the boundary condition on the ideally conducting curved surface $R(\varphi)$ by forcing the tangential electric-field components to zero

$$E_z = 0, \qquad \text{for TM modes} \quad (4)$$

$$E_r \frac{1}{R(\varphi)} \frac{\partial R(\varphi)}{\partial \varphi} + E_\varphi = 0, \qquad \text{for TE modes} \quad (5)$$

provides the cutoff frequencies and the expansion coefficients of the eigenmodes by an iterative procedure [10].

Elliptical waveguide modes can be determined by solving the wave equation in the elliptical coordinate system, which leads to the solutions of the Mathieu and modified Mathieu differential equations [11], [12]. Another way to analyze elliptical waveguides is to apply the BCM method to elliptical cross sections. Both approaches have been realized and lead to identical results. However, the Mathieu solution is more efficient and saves computation time, especially by applying a new power series expansion method to compute the radial Mathieu functions [13]. After the computation of a considerable number of eigenmodes of all waveguide pieces, the MMM can be performed. In detail, this means the calculation of one- and two-dimensional coupling integrals of interacting eigenmodes for each waveguide step and their arrangement in quadratic coupling matrices building up a linear equation system. Its solution represents the electrodynamic characteristic of the discontinuity.

For the computation of the coupling integrals, the different coordinate systems have to be transferred into a basic one. At each step, the applied MMM constrains the integration over the smaller waveguide cross section using its coordinate system as a reference. Considering, for example, a step between a rectangular waveguide with rounded corners and a larger elliptical waveguide, the coordinates of the elliptical waveguide are transformed into the r, φ coordinates of the rectangular waveguide with rounded corners. The eigenmodes of the elliptical waveguide may be expressed by Mathieu functions as well as by computation with the BCM. In the first case, the basic elliptical coordinates have to be converted into the circular coordinates of the rectangular waveguide type, while in the second one, the circular coordinates of the larger (elliptical) cross section have to be transferred into the respective coordinates of the smaller one.[1]

An effective CAD tool for the transition is obtained by the combination of the above MMM with an efficient optimization routine that is based on a modified Newton method [8].

[1]Note, a step of intersecting waveguide cross sections will be handled (as commonly for MMMs) by the introduction of an additional waveguide with zero length surrounding both cross sections.

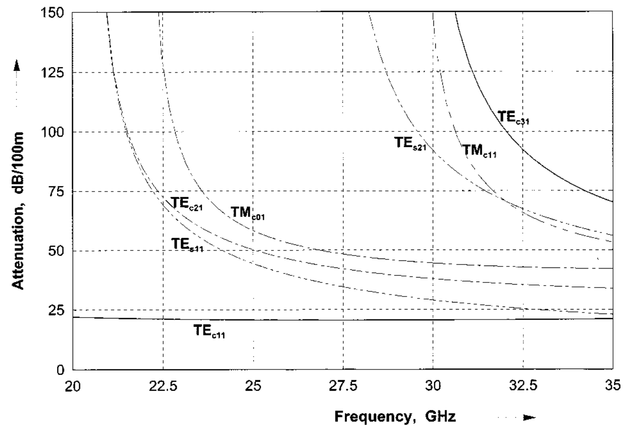

Fig. 3. Mode attenuation characteristics of the A185 waveguide. Solid lines: TE_{c11} fundamental mode and TE_{c31}mode.

To achieve the objective response with few iterations, the sensitivity of all physical parameters, e.g., cross sections and lengths of the waveguide sections, to the electrical characteristics is computed prior to each optimization step for the determination of optimal parameter corrections. The first-order approximation of the sensitivity as the derivative of the yield function with respect to the physical parameters has been proven as sufficient for the prediction of the parameter changes [8].

B. Transitions for Overmoded Waveguide Operation

The application of this CAD tool to the design of high-performance waveguide transitions for the overmoded waveguide operation has to consider proper control of higher order mode conversion within the transition and consideration of measures for higher order mode suppression that might be excited within the waveguide run.

The conversion of a fundamental mode signal into higher order modes within the transition is essentially reduced by the utilization of geometrical symmetry in both axes. Only the TE_{cmn} and TM_{smn} modes having an odd integer of m (e.g. TE_{c31}, TE_{c12}, and TM_{s11}, TM_{s31},and TM_{s12}) will be excited within the transition.

Consequently, a large frequency band can be served by a transition without excitation of higher order modes up to the TE_{c31} cutoff frequency that is typically at 2.6 times the fundamental mode cutoff frequency, as the indicated cutoff frequencies in Fig. 2 show. The utilization of the frequency band above the TE_{c31} cutoff frequency constrains the optimization of the transformer steps concerning minimized TE_{c11} to TE_{c31} mode conversion in addition to the other performance demands. For the complete suppression of the TE_{c31} mode in the overmoded waveguide, not only the conversion factor within the transition is relevant, but also the attenuation difference of the fundamental mode and the dedicated mode. Fig. 3 shows attenuation characteristics of the TE_{c11} (fundamental mode) and the TE_{c31} mode for the overmoded frequency band of the A185 waveguide. For example, a waveguide length of 10 m would improve the TE_{c31} suppression up to 32 GHz by more than 8 dB. Although most mode conversions are avoided by symmetrical transition design, measures have to be introduced for suppression of the higher order modes because weak excitations within the overmoded waveguide may impair the transmission. Commonly, resistive sheets are used for those purposes that are introduced into a transition within the broad axis of the cross section along a length l, similar as introduced in [14]. Despite the perpendicular orientation to the electrical fields of the fundamental mode, the sheet will increase the loss of the transition, which yields an essential drawback in terms of high power-handling capability due to concentrated power dissipation within the transition region. In addition, these designs can only be manufactured by expensive processes, e.g., electroforming or dip electro discharge machining (EDM), since small groves have to be introduced for supporting the sheet.

Higher order mode suppression without insertion loss increase of the fundamental mode can be obtained by introducing waveguide ports within the transition with transverse orientation to the longitudinal axis, dedicated to only couple the higher order modes; similar to wide-band orthomode transducer designs [15]. These transverse ports exhibit rectangular cross sections, providing TE_{10} propagation only within the operational band. A principal transition geometry is depicted in Fig. 4. Three transverse ports are needed for coupling all relevant higher order modes. They are situated perpendicular to the longitudinal axis and symmetrically arranged to the narrow waveguide axis to maintain the properties concerning avoidance of mode conversion within the transition. One port is located in line with the narrow waveguide axis with longitudinal orientation of the cross section. This port couples the longitudinal magnetic-field components of the higher order TE_{cmn} modes with even integer of m and TE_{smn} modes with odd integer of m. The other two ports are in line with the broad wall axis exhibiting parallel orientation of the cross sections with respect to the narrow axis. Consequently, this symmetrical pair of ports couples the TM-field components H_φ of the TM_{cmn} modes with $m = 0$, as well as odd integer of m and also of the TE_{smn} modes with odd integer of m. The waveguides associated with these additional transverse ports are equipped with terminations to dissipate the coupled signals since these ports only serve for higher order mode suppression. This task can be satisfied by moderate matching properties of the coupling functions of the higher order modes to the dedicated port(s). Decoupling of the TE_{10} mode of these ports and the fundamental mode within the transition is obtained due to the orientation of their cross sections.

To achieve effective coupling of the higher order modes to their dedicated transverse ports, the short-circuit planes of the modes within the transformer region have to be computed carefully for the accurate determination of the longitudinal location of the assigned ports. This design is facilitated by the use of a step transformer since it provides nearly constant short-circuit planes for the higher order modes versus the operating frequency band—against the application of smooth tapers.

Optimal coupling of the longitudinal magnetic fields H_z is obtained at the locations with maximum H_z field strength determined by $\lambda_{gi}/4 + n \cdot \lambda_{gi}/2$ with the positive integer n (including zero) and λ_{gi} as the guide wavelength of the dedicated mode i. To accommodate the respective port coupling of several modes with different guide wavelength and short circuit planes,

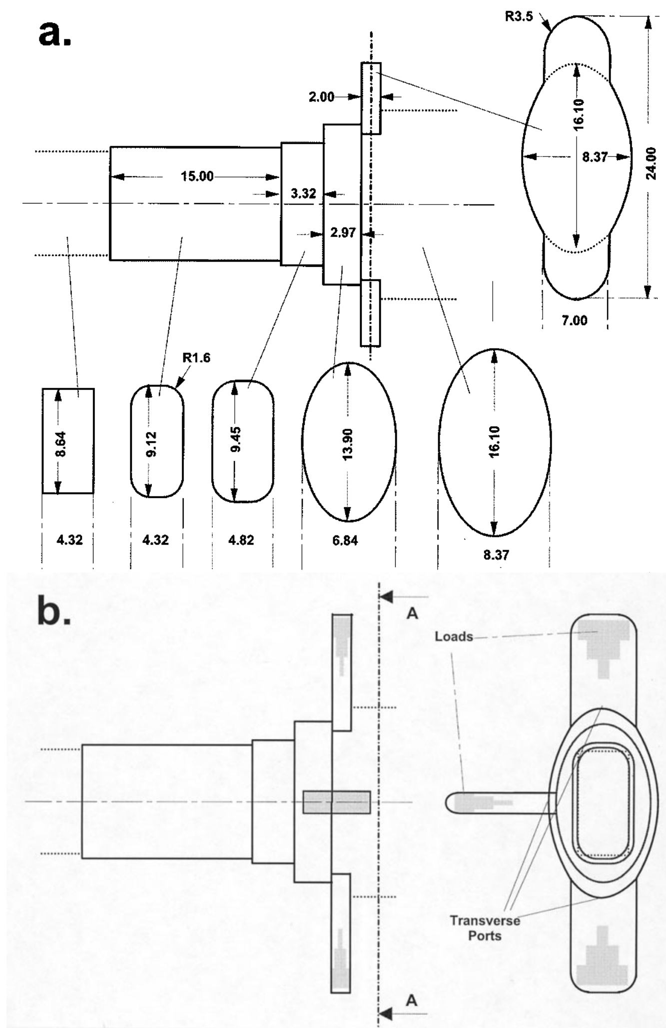

Fig. 4. Overmoded transition design. (a) Computed structure. (b) Principal overall layout sketch.

as in the present application, the first field maximum is chosen, i.e., the location l_{Hz} of the respective transverse port center satisfies $\lambda_{gi}/8 < l < 3 \cdot \lambda_{gi}/8$ yielding sufficient coupling of the dedicated modes to the port.

Similar considerations hold for the symmetrical pair of ports with the locations of maximum TM-field strength H_φ at $n \cdot \lambda_{gi}/2$. These ports are situated as close as possible to the short-circuit planes of the respective modes with the distance $l_{H\varphi}$ of the port center of $< \lambda_{gi}/8$ satisfying the required coupling.

It should be noted that, for these special transition designs, typically two to three transformer sections satisfy the low VSWR demands versus more than 10% bandwidth while maintaining the short-circuit conditions for the higher order modes.

Based on these design aspects, a transition has been optimized with the above-introduced CAD for the overmoded operation of the A185 waveguide at 26 GHz interfacing the WR34 waveguide. The computation has been focused on the transformer design only, considering matching properties and mode conversions of the fundamental mode, as well as the short-circuit planes of the accessible higher order modes. The use of about

20 symmetrical modes for the modal analysis within each section yields satisfactory results.

The initial structure prior to optimization is obtained by considering the transformer sections with linearly decreasing fundamental mode cutoff frequencies from the rectangular waveguide interface port to the elliptical one. The individual lengths of the transformer sections are determined by their dedicated quarter-wavelengths. It should be noted that a relatively long waveguide part with a cross section exhibiting rounded corners has been considered for the interconnection of the WR34 interface and the transformer to facilitate mounting and manufacturing of the transition.

A section with a special cross-sectional shape, shown in Fig. 4(a), is considered between the transformer and A185 waveguide to account for the impact of the symmetrical pair transverse ports on the fundamental mode response. The complete computed structure, depicted in Fig. 4(a), has to be extended by the transverse port with longitudinal orientation. Since this port extends across several sections of the transition, it cannot be considered with acceptable computational expense. However, the port exhibits reduced height (b-dimension) to keep the impact on the fundamental mode response acceptable low, as the results below will show. (Note that the length of the waveguides terminating the transversal ports should be large enough so that the evanescent fields of the fundamental mode extending into the side ports are more than 30 dB subsided to avoid a remarkable impact on the insertion loss of the overall desired transfer function.) The CAD is running on a Sun workstation (ultra sparc2 300 MHz). The computation time for the analysis of the eigenmodes and coupling matrices of the above structure is about 30 min, while the succeeding calculation of the S-parameters is essentially less than 1 s per frequency point.

Owing to the introduction of loads within the side ports, the transition is manufactured from two parts with a transverse cut in the side-port branching region. Consequently, the structure is machined from the flange sides and cutting plane (this design provides a good compromise regarding production expense and required electrical function).

IV. Experimental Results and Overmoded Waveguide Operation

The above transition design for interfacing a WR34 with an A185 waveguide at the RF band of 24.5–26.5 GHz has been realized for the verification of the approach. First, the optimized structure given in Fig. 4(a) with the two symmetrical side ports has been realized to verify the CAD results. Fig. 5 (the complete transition mounted to an A185 waveguide) depicts the favorable compact design approach.

The computed and measured return loss coincide accurately, as the respective curves in Fig. 6 show.[2] In the second step, the transverse port with the longitudinal orientation has been introduced to get the final transition structure [see Fig. 4(b)]. This side port causes only the expected small impact on the return loss, as the comparison of the measured results in Fig. 6 demonstrate.

Fig. 5. Two parts of the transition and the transition mounted to the overmoded A185 waveguide.

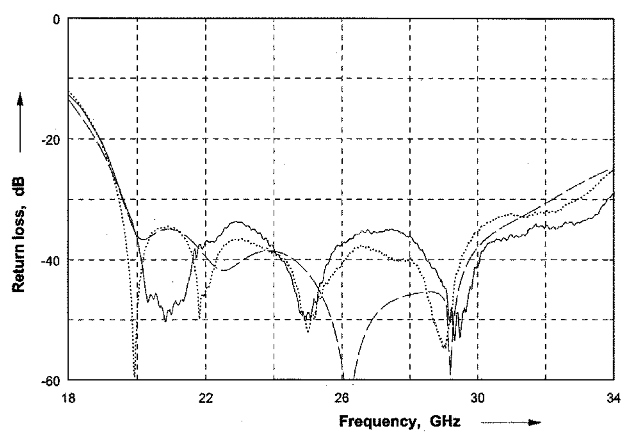

Fig. 6. Computed return loss (dashed line), measured return loss with the two symmetrical side ports (dotted line), and measured return loss of the final overmoded transition (solid line).

The suppression of the higher order modes have been proven with a short overmoded waveguide (length about 0.5 m) that has been equipped with two transitions of the above design for interfacing the standard WR34 waveguide. The first insertion loss measurement (Fig. 7) has been performed without any means for higher order mode suppression. The curve exhibits many spikes resulting from weak higher order mode excitations that resonate within the overmoded waveguide.

Another test has been performed with absorbing sheets introduced into the transitions perpendicular to the fundamental mode E-field components, similar to [14]. The measured result is depicted in Fig. 8(a). First, an increased insertion loss of about 0.15 dB versus the complete band is obvious. Secondly, few spikes in the upper part of the frequency band can be noticed that may result from TE_{c21} excitations because this mode is not suppressed by the absorbing sheets and the decreasing insertion

[2]For precise measurements, the network analyzer has been calibrated with WR34 standards; the return-loss measurements have been performed with a precision A185 sliding load; thus, VSWR values in the order of 1.01 could be verified.

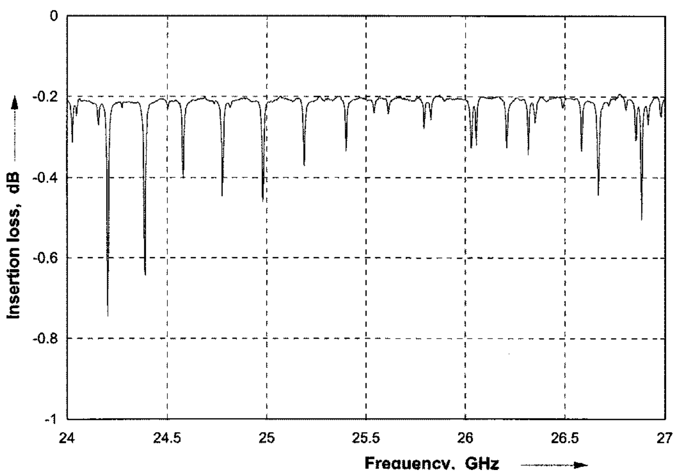

Fig. 7. Measured insertion loss of a short overmoded operated waveguide (length about 0.5 m)—transitions without any means for higher order mode suppression.

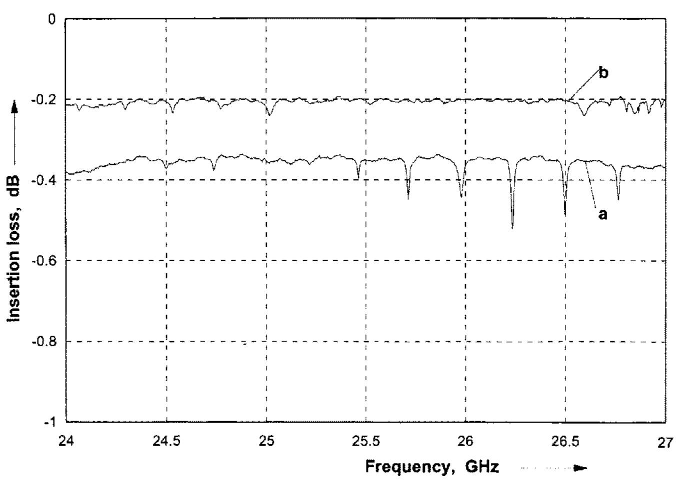

Fig. 8. Measured insertion loss of the short overmoded operated waveguide above with transitions. (a) Equipped with absorbing sheets. (b) Sidewall ports equipped with loads.

loss versus frequency of this mode is not sufficient for the attenuation of these resonant spikes. Thus, solutions using absorbing sheet mode filters are only applicable for longer waveguides, typically >10 m, where the insertion loss of the TE_{c21} is high enough to attenuate such spikes.

Finally, the transitions have been equipped with the loads in the transverse branching side ports. The measured insertion loss of this approach is shown in Fig. 8(b). Sufficient higher order mode suppression is obtained within the complete operating frequency band, even for such short waveguide lengths, while the insertion loss exhibits nearly the same low value achieved without any absorbing means in Fig. 7.

V. Conclusions

A transition design for interfacing rectangular waveguides with elliptical waveguides has been introduced in this paper, focusing on the overmoded operation at the elliptical waveguide port. The particular considerations imposed on such transition design, namely, higher order mode control, low VSWR, and insertion loss, as well as low manufacturing expense, are outlined. To cope with all these demands, the design is supported by a suitable CAD tool that proves good agreement of computed and measured results. The overmoded waveguide approach is verified by experimental results of a millimeter-wave application at 26 GHz. Consequently, overmoded operated waveguide systems with considerable lower insertion loss than standard ones can be provided with high-performance properties for high-capacity radio relay systems, as well as high-power earth stations, even for millimeter-wave applications.

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