Analysis of Modes in Rectangular-Waveguide Noncontacting Shorting Plunger

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Short Abstract—Modes propagating and resonating in a structure consisting of a section of R26 rectangular waveguide that houses a noncontacting brick-shaped shorting plunger have been analyzed with the assistance of an electromagnetic field solver. Effects of plunger waggle have also been investigated. Spurious resonances of modes trapped within the plunger-filled section deteriorate the short performance. The analysis serves as a preliminary work in an attempt to design a resonance-free noncontacting sliding short.

Keywords—noncontacting backshort; sliding short; waveguide components; industrial applications

I. INTRODUCTION

The sliding waveguide short is a useful and frequently utilized component in high-power industrial microwave installations. Contacting plungers have obvious disadvantages in wear and unreliable contact with the main waveguide, whereas the use of noncontacting shorts has been hindered by the existence of resonant dips in reflection coefficient within the operating frequency range. An overview of sliding shorts and problems associated with them can be found e.g. in [1]. The spurious resonances may be “stubborn” in the sense that they cannot be removed by for instance changing the plunger length or incorporating a standard microwave choke. The reflection dips are accompanied by peaks in transmission behind the shorting block, directing a substantial portion of the microwave power into a short-motion mechanism (which may lead to its damage) or into the environment (presenting health hazard). The resonances are caused by modes that can propagate within the plunger-filled waveguide section [2]. The excitation of the modes depends on the plunger offset and rotation from its ideally centered position (waggle). An experiment-based investigation for a specific, millimeter-wave case was undertaken in [2]. No effective software tools were available at the time to address the subject otherwise. The present analysis has been carried out in order to better understand the nature of these resonances and will serve as a starting point for the design of a high-power resonance-free waggle-tolerant noncontacting sliding short. The investigations have been fundamentally assisted by a full-wave electromagnetic field simulator (CST Microwave Studio [3]). The paper objectives are:

- To classify modes of electromagnetic waves that can exist in the plunger-filled waveguide.
- To discuss the modes that can propagate in 2 – 3 GHz band.
- To present their basic field distribution and give their cutoff frequencies as well as conversion coefficients from the TE$_{10}$ mode in an empty waveguide.
- To investigate effects of plunger waggle.
- To analyze and discuss resonances that fall into 2 – 3 GHz band and draw some general conclusions.
- To discuss the behavior of a conventional microwave choke.

II. ANALYZED STRUCTURE

The analyzed structure (Fig. 1) consists of a brick-shaped perfectly conducting plunger of length $L$ placed in a section of R26 waveguide (cross-sectional dimensions $a = 86.36$ mm, $b = 43.18$ mm). Ideally, the plunger sides are parallel with the waveguide walls and the plunger is cross-sectionally centered so that the gap between it and all guide walls is equally $s = 2$ mm.

A slightly modified structure with a semi-infinite plunger has been used for the analysis of propagating modes and their excitation by empty-guide TE$_{10}$: one plunger face has been extended up to the guide end, thus forming a section of TEM

Figure 1. Analyzed structure.
transmission line with TEM output (dashed line in Fig. 1). To simulate waggling, the ideal plunger position was perturbed by x- and y-direction offsets of \(x_0 = 0.5\) mm and \(y_0 = 0.5\) mm, respectively, and a rotation around the guide z-axis by \(\alpha = \pm 0.5^\circ\). All the combinations have been considered.

### III. Modes in Plunger-Filled Waveguide

In direct analogy with a cylindrical coaxial transmission line [4] having the gap thickness \(s\) and the mean gap circumference \(d = 2(a + b) - 4s\) equal to those of the plunger-filled waveguide, the modes existing in the waveguide can be under a small-gap assumption (\(s \ll d\)) categorized as follows:

- TEM mode;
- Low-frequency TE modes;
- High-frequency TE modes;
- TM modes.

#### A. TEM Mode

The TEM mode has zero cutoff frequency: once excited, it can propagate in the structure.

#### B. Low-Frequency TE Modes

The low-frequency TE modes have the cutoff wavelengths given approximately by

\[
\lambda_c = d/m, \quad m = 1, 2, \ldots
\]  

The formula implies that a multiple (\(m\)) of free-space wavelengths must fit in the gap circumference at cutoff frequency \(f_c\). The modes will be designated TE\(_{m0}\). The second subscript (0) reflects the fact that the field varies slowly in radial direction (no oscillatory character with half-wavelength periodicity). Since \(d\) is comparable to the main guide dimensions \(a, b\), several such modes can propagate in the frequency range of interest.

For each \(m\) there are actually two TE\(_{m0}\) modes: their field patterns appear “rotated” around the guide’s z-axis by \(90/m\) degrees, and their cutoff frequencies are close to each other. This is again analogous to the higher-order modes in a coaxial line where two axially rotated but otherwise identical degenerate modes account for all possible polarizations. We will distinguish the members of such mode couple by additional letters a, b: TE\(_{a0}\) and TE\(_{b0}\).

#### C. High-Frequency TE Modes and TM Modes

The high-frequency TE modes as well as (all) TM modes have cutoff wavelengths given approximately by

\[
\lambda_c = 2s/n, \quad n = 1, 2, \ldots
\]  

The modes are oscillatory in radial direction in that \(n\) free-space half-wavelengths fit in the gap thickness \(s\) at cutoff frequency. For millimeter-wide gaps this implies cutoff frequencies in millimeter-wave range (hence the designation high-frequency modes). The modes are therefore insignificant in the studied context.

#### D. Basic Mode Properties

Accurate values of \(f_c\) as well as field patterns and conversion coefficients from the empty-guide TE\(_{10}\) mode have been obtained by the electromagnetic simulator. The results have revealed that besides TEM, up to four TE modes can propagate in the plunger-filled section. Their E-field patterns (except the obvious TEM) are illustrated in Fig. 2; a summary of their basic properties is given in Table I. The quantities marked “ideal” correspond to ideal plunger position, the quantities with subscripts min and max are limits for the plunger position perturbed (waggled) in the manner specified above. The cutoff frequencies vary by more than 50 MHz when the plunger is waggled. For TE\(_{20}\) modes, \(f_c\) are close to or within the ISM band (2.4 – 2.5 GHz), which is the source of the problems, as will be explained below.

![Figure 2. E-field of propagating TE modes in the plunger-filled guide.](image)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>TEM</th>
<th>TE(_{a10})</th>
<th>TE(_{b10})</th>
<th>TE(_{a20})</th>
<th>TE(_{b20})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_c) (GHz) – ideal</td>
<td>0</td>
<td>1.198</td>
<td>1.206</td>
<td>2.396</td>
<td>2.411</td>
</tr>
<tr>
<td>(f_{c\text{ min}}) (GHz)</td>
<td>0</td>
<td>1.138</td>
<td>1.190</td>
<td>2.340</td>
<td>2.395</td>
</tr>
<tr>
<td>(f_{c\text{ max}}) (GHz)</td>
<td>0</td>
<td>1.203</td>
<td>1.263</td>
<td>2.402</td>
<td>2.452</td>
</tr>
<tr>
<td>(\Delta f_c) (MHz)</td>
<td>0</td>
<td>65</td>
<td>73</td>
<td>62</td>
<td>57</td>
</tr>
<tr>
<td>(C) (dB) – ideal</td>
<td>-</td>
<td>-6.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(C_{\text{max}}) (dB)</td>
<td>-30.8</td>
<td>-6.0</td>
<td>-8.3</td>
<td>-16.2</td>
<td>-16.2</td>
</tr>
</tbody>
</table>

\(C\) is conversion coefficient from empty-guide TE\(_{10}\) mode at 2.45 GHz. In case of ideal plunger position, only TE\(_{a10}\) mode, whose field pattern conforms that of TE\(_{10}\), is excited – strongly. (A consequence is that a potential choke should be designed for this mode rather than for the intuitively preferred TEM.) However, when perturbing the plunger position, mode symmetries evident in Fig. 2 will be lost, and more or even all of the modes will be excited. \(C_{\text{max}}\) is the maximum conversion coefficient in the frequency range 2 – 3 GHz for all the plunger offset and rotation combinations. Considering this, a choke design becomes ambiguous, if only due to differing
wavelengths of the individual modes.

E. Surface Currents

Fig. 3 shows “snapshots” of longitudinal magnetic field components $H_z$ of the propagating TE modes. Dark and white areas mark the locations of maximum field strength (with opposite polarities of $H_z$). With time, the patterns move along the waveguide axis. The importance of $H_z$ lies in the fact that it is proportional to transverse surface currents. Suppressing these currents e.g. by longitudinal slots made at their maxima can provide a method of how to suppress or influence the TE mode patterns without much affecting the TEM mode.

IV. PLUNGER RESONANCES

Modes of propagation trapped in the plunger-filled waveguide portion of Fig. 1 give rise to resonances that exhibit themselves as peaks/dips in the frequency response of transmission coefficient magnitude $|S_{21}|$. Except the modes independent of the plunger length $L$ (those will be treated separately) the plunger-filled waveguide section can be approximately viewed as a transmission line almost open-ended at both sides, effectively longer than $L$ by an amount $\Delta L$ due to fringing fields evanescent in the empty guide. In view of this, relation between a resonance frequency $f_r$ and cutoff frequency $f_c$ of an ideally positioned plunger can be approximated by

$$f_r^2 = f_c^2 + c^2 \left[ \frac{p}{2(L + \Delta L)} \right]^2 \quad p = 1, 2, ... \quad (3)$$

where $c$ is light velocity and $\Delta L$ is the length correction factor. The subscript $p$ will be added to the resonance mode designations ($TE_{m0p}$, $TE_{m0p}$).

In order to investigate the resonances, a plunger of length $L = 50$ mm has been simulated. Unlike the previous study of propagating modes, when the structure had to be (piecewise) homogeneous in $z$-direction, the plunger position could now be additionally perturbed by swaying it around the $x$- and $y$-axes (angles $\alpha_x = \pm 0.5^\circ$, $\alpha_y = \pm 0.5^\circ$ have been used in the computations).

Examples of $|S_{21}|$ for the plunger in the ideal position (thin curve) and the plunger offset by 0.5 mm simultaneously in $x$- and $y$-directions (thick curve) are shown in Fig. 4. (Rotating the plunger does not qualitatively affect the situation.)
A. Modes Dependent on Plunger Length

The case with the ideally positioned plunger exhibits only one, broad (due to the strong coupling) peak located at 2.925 GHz. It corresponds to the only excited mode, TEa_{10}, resonating so that approximately one half of the standing wavelength is distributed along the plunger length \( p = 1 \). The mode designation is therefore TEa_{101}. Offsetting the plunger preserves this main peak but gives rise to four additional peaks of nearly total transmission. The one with the highest frequency (2.88 GHz) corresponds to the twin mode TEb_{101}. (The peak is narrow because in this particular case the coupling to empty guide is weak – about -35 dB.)

The resonance located at 2.54 GHz is TEM with \( p = 1 \) (TEM_1).

Varying the plunger length necessarily varies the resonant frequency of each of the above three modes: by proper choice of \( L \) the peaks can be moved outside of the operating range.

B. Modes Independent of Plunger Length

The two closely spaced peaks located at 2.445 GHz and 2.448 GHz (see the inset in Fig. 4) correspond to resonance modes TEa_{200} and TEb_{200}, respectively (\( p=0 \)). In contrast to the previous cases, their field amplitude does not oscillate along the plunger length. The standing wave pattern can be imagined as set up from two opposite TEM waves, nearly uniform along \( z \)-direction, traveling circumferentially around the plunger, the plunger being terminated by imperfect magnetic walls at its ends. In case of perfect magnetic walls (ideal open circuits) the resonance frequencies would truly be independent of the plunger length \( L \) and (3) could be used with \( p=0 \). The reality is better approximated by

\[
f_c^2 = f_c^2 + \left( \frac{c\delta}{2L} \right)^2
\]

(4)

where \( \delta < 1 \) is a correction factor accounting for the fringing-field effects. In our case, the equation is applicable for \( L \geq 30 \) mm. Since a typical value of \( \delta \) is 0.01, the resonant frequencies depend only little on plunger length, nearly coinciding with the cutoff frequencies \( f_c \).

Although derived for a specific case of R26 waveguide, these conclusions are valid quite generally. Incidentally and unfortunately, it is just the R26 waveguide for which these “obstinate” resonances fall exactly into the 2.45 GHz ISM band. Varying the gap thickness (the only parameter available) makes little sense due to its limited effect on \( f_c \).

C. Microwave Choke

To attenuate an unwanted wave, a microwave choke can be embedded in the plunger as shown in Fig. 5. It is in principle a band-stop filter implemented as a series-connected short-ended transmission line section one quarter-wavelength long, transforming the terminating short to an open at its input. The “wavelength” here means the choke interior guide wavelength of the mode to be suppressed. Such choke can therefore suppress only one of the modes (more if their wavelengths are close). This is nominally the case of a plunger in an ideal position, when only TEa_{10} is excited. When the tuner is waggled and up to five modes can be excited, the choke will also attenuate the twin TEa_{10} mode. It will not suppress the TEM but this mode’s resonance can be tuned out by properly choosing the plunger length \( L \); the remnant off-resonance TEM leakage in the operating band can be tolerable.

However, such choke will by no means suppress the TEa_{20} and TEb_{20} modes. It is because close to \( f_c \) the guide wavelength approaches infinity: any choke with a practical length transforms the terminating short to a short again, making thus the choke electrically nonexistent. These two modes, which could neither be tuned out by plunger length nor suppressed by a choke, constitute the main obstacle in designing a good noncontacting short. Ways to cope with the problem are yet to be found. A possible solution may lie in suppressing the TE modes by blocking their transverse surface currents by introducing longitudinal slots in the plunger surface, and tuning the choke for the only remaining TEM mode.

V. CONCLUSIONS

With the assistance of an electromagnetic field simulator, modes of propagation and resonances in an R26 waveguide loaded with a noncontacting rectangular shorting block have been analyzed, and some general conclusions have been drawn. Two resonances, designated TEa_{20} and TEb_{20}, excited when the plunger is not strictly centered in the waveguide, have been found critical for the short performance. The resonances can neither be tuned out by changing the plunger length nor suppressed by a conventional choke because the resonant frequencies are practically fixed at cutoff frequencies of the corresponding modes of propagation, which for R26 waveguide incidentally fall into the 2.45 GHz ISM band. The analysis has helped to properly understand the nature of the problem and is believed to be a starting point to its solution.
REFERENCES


