Resonance transmission of small narrow slots loaded with two parallel wires in a conducting screen

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Abstract: This paper presents the resonance transmission of a small, narrow slot in a conducting screen with two parallel wires. When a plane wave excites the slot, the aperture magnetic current is controlled by the wires connected across the slot. Parallel-wire-loaded slot resonance can occur, which is known as a transmission resonance or extraordinary transmission. In this case, the electromagnetic power transmitted through the slot with the wires is much larger than that when the wires are not present. The results show that the wires result in the maximum power transmission (resonance transmission or extraordinary transmission). The resonant frequency of a 3-cm slotted structure can be reduced from 4.56 GHz to various desired frequencies by adding the wires.

Keywords: small narrow slot, resonance transmission, extraordinary transmission, two parallel wires, transmission cross section

Classification: Microwave and millimeter-wave devices, circuits, and modules

References


1 Introduction

For many years, many studies have investigated the penetration of electromagnetic fields and wave transmission through a slot aperture in a conducting screen [1, 2, 3, 4, 5]. The reduction problem of the electromagnetic field penetration through a half-wavelength narrow slot has been studied in the field of Electromagnetic Compatibility (EMC) as an aperture cutoff filter [6, 7]. A very small amount of electromagnetic waves are transmitted through a small slot. Harrington explained the resonance transmission by placing a capacitor across the midpoint of the aperture [8]. To obtain high transmission efficiency for an electrically small aperture, the transmission resonance phenomenon is obtained by deforming the shape of the aperture [9, 10, 11, 12, 13, 14, 15].

This paper investigates the transmission resonance phenomenon to obtain high transmission for an electrically small aperture as an aperture pass filter. The resonance transmission through a small, narrow slot is described for when two parallel wires are installed on the slot aperture. The integral equation for the magnetic current on the narrow slot aperture was derived and solved by applying Galerkin’s method of moments (MoM). When a plane wave excites the small slot,
the aperture magnetic current is controlled by the two parallel wires, and the maximum power transmission (resonance transmission or extraordinary transmission) occurs at a given frequency.

The results show that the resonance transmission of the penetrated electromagnetic power is effectively obtained by using the parallel wires. By adding the wires, the resonant frequency of a 3-cm slot-loaded structure can be reduced from 4.56 GHz to various desired frequencies of 1 GHz (78.1%), 2 GHz (56.1%), and 3 GHz (34.2%). To verify the theoretical analysis, the calculated transmission cross sections were compared with experiments.

2 Theoretical analysis

Fig. 1 shows the structure of an infinitely large conducting screen with a small, narrow slot. Fig. 1(a) shows the slot without two parallel wires, and Fig. 1(b) shows the slot with two parallel wires of length \( h \). The conducting screen is located on the \( xy \)-plane with the origin at the center of the slot aperture. The wires are connected along the \( x \)-axis by a distance \( d \) and are parallel to the \( z \)-axis. The problem can be divided into two regions, as illustrated in the figure. Region I \((z < 0)\) is defined as the half-space containing the incident plane wave \( \vec{E}_i \) and bounded by the conducting screen. The incident electromagnetic fields penetrate into Region II \((z > 0)\), and the two regions are assumed to be free space.

A magnetic current sheet with width \( b \) can be replaced by a magnetic current cylinder with an equivalent radius of \( b = 4 \), where \( b \) is much smaller than the wavelength \([6]\). The unknown aperture magnetic current is

\[
\vec{M} = \frac{1}{j \omega \mu_0} \int_S \left( \vec{K}_m \cdot \vec{M} \right) dS_a + \frac{1}{j \omega \mu_0} \int_S \left( \vec{K}_m \cdot \vec{M} \right) dS_a
\]

(1)

where

\[
\vec{K}_m (\vec{r}, \vec{r}') = (\vec{k}^2 + \nabla \nabla) \cdot \vec{G}_m (\vec{r}, \vec{r}')
\]

(2)

\[
\vec{H}^{SC} = -\frac{2}{\eta} E_{0y}
\]

(3)

\( \vec{H}^{SC} \) is the short-circuited magnetic field when the slot aperture is covered by a conducting plate. \( E_{0y} \) is the amplitude of the incident electric field, and \( \eta \) is the wave impedance of free space. \( \vec{k} \) is a unit dyadic, \( \delta(\cdot) \) is the Dirac delta-function, \( k = \omega \sqrt{\mu_0 \varepsilon_0} \), and \( \omega \) represents the angular frequency. The superscripts I and II denote the corresponding regions. \( \hat{y} \) and \( \hat{z} \) are unit vectors in the \( y \) and \( z \) directions. The position vectors \( \vec{r} \) and \( \vec{r}' \) correspond to the observation and source points, respectively.

d\( S_a \) denotes an area element on the slot aperture, and \( \vec{K}_m^I \) and \( \vec{K}_m^{II} \) are the dyadic Green functions of the half-space. The time dependence \( \exp(j\omega t) \) is assumed and omitted throughout this paper. \( I_y \) is the current at the connecting position
of the two parallel wires. \( V_L \) is the voltage of the loading point, and \( Z_L \) is the impedance of the two parallel wires, which can be expressed as:

\[
Z_L = -j 120 \ln \left( \frac{s}{r} + \sqrt{\left( \frac{s}{r} \right)^2 - 1} \right) \cot(\beta h)
\]

(4)

where \( \beta \) is the propagation constant of the wires. \( s = b/2 + r \) and \( r \) denote the half-spacing and radius of the wires, respectively.

To solve the integral equation for the unknown, the aperture magnetic current \( \tilde{M} \) is expanded into piecewise sinusoidal expansion functions. Using Galerkin’s method of moments, we can obtain a set of linear equations for the unknown expansion coefficients.

When a plane wave excites the slot aperture, the transmission coefficient of the slot is defined as follows:

\[
TC = \frac{P_{\text{tra}}}{P_{\text{inc}}}
\]

(5)

where \( P_{\text{tra}} \) is the average power transmitted through the slot, and \( P_{\text{inc}} \) is the average power incident on the slot:
where \( A \) is the area of the slot, the asterisk denotes complex conjugation, and \( H_{0x}^i \) is the incident magnetic field.

When a plane wave excites the slot aperture, the transmission cross section (TCS) of the slot is defined as the area for which the incident wave contains the power transmitted by the slot. It follows that the transmission cross section is equal to \( TC \times A \).

\[
TCS = TC \times A = \frac{P_{tra}}{\eta |H_{0x}^i|^2} \quad [m^2] \tag{8}
\]

The transmission cross section \( TCS \) at resonance (8) becomes \( 3\lambda^2/4\pi \) (= \( 2G\lambda^2/4\pi, \ G = 1.5 \)). For an electrically small antenna, the maximum absorption area is equal to \( 3\lambda^2/4\pi \). If the slot resonates at around half the wavelength, the transmission cross section \( TCS \) becomes \( 3.28\lambda^2/4\pi \) (= \( 2G\lambda^2/4\pi, \ G = 1.64 \)). For an electrically small slot, the amount of waves transmitted through a small slot is very small, and we show the effects of two parallel wires on \( TCS \).

### 3 Numerical results and discussion

The slot used in the calculation is a small and narrow compared to the wavelength. The dimensions of the slot are \( a = 3 \) cm and \( b = 1 \) mm. Frequencies of 1 GHz, 2 GHz, and 3 GHz are used to consider \( TCS \) of the slot. Fig. 2 shows the \( TCS \) for a narrow slot of \( a = 3 \) cm and \( a = 15 \) cm without the two parallel wires (Fig. 1(a)). As shown in Fig. 2(a), the maximum transmission (\( TCS = 11.128 \) cm\(^2\)) for \( a = 3 \) cm occurs at the resonant frequency of 4.56 GHz. For \( a = 15 \) cm, the maximum transmission (\( TCS = 259.985 \) cm\(^2\)) occurs at the resonant frequency of 0.94 GHz, as shown in Fig. 2(b). Fig. 2 also shows that \( TCS = 3.28\lambda^2/4\pi \) (= \( 2G\lambda^2/4\pi, \ G = 1.64 \)), which is the maximum \( TCS \) for the resonant source. Thus, the predicted maximum transmission cross sections of the slot with \( a = 3 \) cm are 234.91 cm\(^2\) at 1 GHz, 58.728 cm\(^2\) at 2 GHz, and 26.101 cm\(^2\) at 3 GHz. However, because slot is small and narrow at these frequencies, the transmission power is very low, as shown in Fig. 2(a): \( TCS = 0.001 \) cm\(^2\) at 1 GHz, 0.026 cm\(^2\) at 2 GHz, and 0.261 cm\(^2\) at 3 GHz. This paper shows that the maximum transmission (known as resonance transmission or extraordinary transmission) for a slot with \( a = 3 \) cm at these frequencies can be effectively obtained by using the two parallel wires.

Fig. 3 shows \( TCS \) of the slot versus the length of the two parallel wires for different wire positions when a plane wave with frequencies of 1 GHz, 2 GHz, and 3 GHz is incident on the narrow slot aperture. The resonance transmissions occur at \( h = 0.218\lambda \) (\( h = 6.542 \) cm) for 1 GHz, \( h = 0.179\lambda \) (\( h = 2.6955 \) cm) for 2 GHz, and \( h = 0.1294\lambda \) (\( h = 1.294 \) cm) for 3 GHz when the wires are connected at \( d = 0 \) cm (the center of the slot). The \( TCS \) for the case with wires case gives rise to resonance transmission (known as forced resonance), which is equal to \( 3\lambda^2/4\pi \) (= \( 2G\lambda^2/4\pi, \ G = 1.5 \)) for a Hertzian source [8]. As shown in Fig. 3, the \( TCS \) is
enhanced to $3\lambda^2/4\pi$ (214.86 cm$^2$ at 1 GHz, 53.72 cm$^2$ at 2 GHz, and 23.87 cm$^2$ at 3 GHz) by using wire lengths of around $0.12\lambda$ to $0.23\lambda$ for wire positions of $d = 0$–1.5 cm. If the two parallel wires are connected on the end of the slot aperture ($d = 1.5$ cm), the TCS is not enhanced. In this case, the result is the same as the case with no parallel wires.

Fig. 4 shows the frequency characteristics of the TCS for a slot length of 3 cm when two parallel wires of length 6.542 cm are connected at $d = 0$ cm for 1 GHz, 2.696 cm for 2 GHz, and 1.294 cm for 3 GHz. The dashed line indicated with “original slot” represents the TCS when no parallel wires are present on the slot, and the maximum TCS (11.128 cm$^2$) occurs at a frequency of 4.56 GHz. This frequency corresponds to the resonance frequency of a narrow slot with a length of 3 cm. The solid lines indicated with “loaded slot” show the TCS for 1 GHz, 2 GHz, and 3 GHz when the two parallel wires are connected at $d = 0$ cm on the slot. The TCS is effectively enhanced to $3\lambda^2/4\pi$ by the wires, as shown in Fig. 4.

The TCS for each case is also given in Table I. Table I and Fig. 4 show that the resonance transmissions (maximum transmission or extraordinary transmission) of the slot occur as a result of the loaded capacitive reactances on the narrow slot.
aperture, and $TCS$ is enhanced to $3\lambda^2/4\pi$. The resonant frequency can be reduced from 4.56 GHz to various desired frequencies of 1 GHz (78.1%), 2 GHz (56.1%), and 3 GHz (34.2%) by adding the wires.

Experimental results are provided to validate the numerical calculations. Fig. 5 shows a photograph of the experiment setup for measuring the transmission

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**Fig. 3.** Transmission cross sections versus length of the two parallel wires for different wire positions at (a) 1 GHz, (b) 2 GHz, and (c) 3 GHz.
characteristics of the slot-loaded structure. A large ground plane (2 × 4 m) is attached to a small, narrow slot (3 cm × 1 mm) in an anechoic chamber. Two parallel wires with a radius of 0.5 mm made from copper are connected at the center of the narrow slot as a capacitive reactance. Broadband double-ridged horn antennas made by ICU (model No. ICU-MA-04-2, 0.75–6 GHz) were used as the transmitting and receiving antennas. The S-parameters are measured by the antennas under normal incidence and a Wiltron 37225A vector network analyzer.

Table 1. The enhanced TCS and loading reactances.

<table>
<thead>
<tr>
<th>Transmission resonance frequency (GHz)</th>
<th>TCS (cm²)</th>
<th>$3\lambda^2/4\pi$ (cm²)</th>
<th>Two parallel wires (reactance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$h/\lambda$</td>
</tr>
<tr>
<td>1.0</td>
<td>215.96</td>
<td>214.86</td>
<td>0.2181</td>
</tr>
<tr>
<td>2.0</td>
<td>54.336</td>
<td>53.715</td>
<td>0.1797</td>
</tr>
<tr>
<td>3.0</td>
<td>24.677</td>
<td>23.873</td>
<td>0.1294</td>
</tr>
</tbody>
</table>

Fig. 4. Transmission cross section versus frequency for different wire lengths of $h = 6.542$ cm, $h = 2.696$ cm, and $h = 1.294$ cm connected at the slot center.

Fig. 5. Photograph of the experiment setup.
The antennas were placed 100 cm away from the structure to satisfy the far field condition.

The measured and calculated transmission coefficients $TC$ are shown in Fig. 6. We examined the resonance transmission at a frequency of $3.38 \, \text{GHz} \ (h = 1.28 \, \text{cm})$ to confirm the resonance transmission of the slot resulting from the loading reactance on the slot aperture. The calculated transmission coefficients are in reasonable agreement with the experimental results with about 6% frequency shift. The experimental and theoretical results show that the resonance transmission of the slot is effectively enhanced by the wires. There are little differences and fluctuations in the magnitudes of the measured transmission coefficients. These are mainly caused by fabrication and alignment errors, mutual coupling effects between the horn antenna and the ground plane, and losses of the ground plane.

4 Conclusion

This paper presented the resonance transmission (maximum transmission or extraordinary transmission) of electromagnetic waves through a loaded slot structure on an infinite conducting screen. $TCS$ can be enhanced by adjusting the length of the two parallel wires on the slot aperture. Resonance transmission occurs as a result of connecting a capacitive reactance to the slot aperture at a given frequency. Therefore, the two parallel wires are an effective way to enhance the electromagnetic transmission through the slot in a planar conducting screen.

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