Shielding Effectiveness of Modern Energy Saving Windows

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Before starting my talk I would like to pay tribute to my colleagues from Centre for Physical science and technology Dr. Paulius Ragulis, Dr. Rimantas Simniškis and magister student Evaldas Bilotas, as well as colleagues from Sweden eng. Bengt Vallhagen, and Dr. Mats Bäckström from Saab Aeronautics, Linkoping and PhD student Per Ängskog from KTH, Stockholm, who participated in the investigation that will be presented today.
The first part of my talk will be devoted to the investigation of the shielding effectiveness of modern energy saving (low-E) windows. These investigations has been recently published in the paper P. Ragulis, P. Ängskog, R. Simniškis, B. Vallhagen, M. Bäckström, and Ž. Kancleris, “Shielding effectiveness of modern energy-saving glasses and windows,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 8, pp. 4250-4258, 2017.

The second part of my talk will be devoted to the minimization or maximization of the shielding effectiveness in a double-glazed modern low-E window.
1. Introduction.
2. Experimental setups.
4. Shielding effectiveness of single, double and triple glazed low-E windows.
5. How to get minimum or maximum shielding effectiveness?
6. Experimental confirmation.
7. Example for Wi-Fi frequency band.
8. Conclusions.
Example of triple silver low-E coating from http://kierantimberlake.com/posts/view/242. Effective reflection back of solar heat and inside radiant heat by multilayered structure consisting of silver layers in between the dielectric metal oxide layers. In the microwave region the structure can be considered as a single metal layer with an effective surface conductivity $\sigma$. 

### Introduction

- **Solar heat**
- **Low-E Coating**
- **Air Space**
- **Glass**

**TRIPLE SILVER LOW-E COATING**

- **Total Thickness 225-250 nm**

- **Layers:**
  - 1-4 nm MOX Dielectric Protective Layer
  - 20-40 nm MOX Dielectric Top Coat
  - 5-6 nm MOX Dielectric
  - 1-2 nm M - OX Protective Layer
  - 10-15 nm Silver
  - 65-90 nm MOX Dielectric
  - 1-2 nm M - OX Protective Layer
  - 10-12 nm Silver
  - 65-90 nm MOX Dielectric
  - 1-2 nm MOX Dielectric Protective Layer
  - 10-12 nm Silver
  - 20-30 nm MOX Dielectric Base Coat
Reasons to investigate energy saving windows

- Modern low-E windows demonstrate significant shielding effectiveness at microwave frequency range.
- Direct calculation of shielding effectiveness using numerical methods is complicated even though the parameters of each conducting and dielectric layer are known. Usually they are not known, because glass producers are protecting know-how and not disclosing details about low-E coating layers.
- Therefore experimental investigation, as well as the simplified models allowing efficiently calculate the shielding effectiveness of modern energy saving windows should be of great importance for designers of modern microwave communication systems working at urban environment.
Experiments have been performed in the anechoic chamber at the Center for Physical Sciences and Technology. Saint Gobain company samples were investigated, their size $20 \text{ cm} \times 30 \text{ cm}$.

Investigated sample was decorated with absorbers.
The anechoic chamber (8.4 m × 4.6 m × 3.7 m) with antenna and decorated sample.
Experiments have been performed using aperture on the wall of the semi-anechoic chamber at SAAB Aeronautics. It was covered by Saint Gobain company samples, their size 30 cm × 30 cm.

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Incident $P_i$ and transmitted through the sample power $P_t$ was measured and transmittance $T$ was calculated

$$T = \frac{P_t}{P_i}$$

From $T$ shielding effectiveness was calculated in dB units.

$$SE = 10 \log \frac{1}{T} \quad \text{[dB]}$$

in dB units.
I have presented calculation procedure two years ago in 16th Lithuanian-Belarus workshop. Today I only remind you that it is based on the concept of the surface conductivity of a thin metal layer covering surface of the dielectric.

- Tangential component of the electric field is continuous through the interface, whereas tangential component of the magnetic field undergoes break that is proportional to the surface current that flows in the interface.

\[ \eta_i \text{ impedance of the layer} \]
• This allows us to write up a matching matrix of the interface accounting for its surface conductivity $\sigma_i$, and compute the amplitude of the transmitted wave through the system of the dielectrics having conducting layers at the interfaces in a rather simple and fast way – by multiplying matching and propagation matrices. To calculate the transmittance of a double-glazed window you need to multiply seven $2 \times 2$ matrices. The only unknown parameter of such a calculation is a surface conductivity of the interface which can be determined by fitting the calculated shielding effectiveness dependence on frequency with experimentally measured.
Fabry-Perot resonance dielectric slab

• Before going to present results of experiments and calculations I would like to remind you phenomenon of Fabry-Perot resonance in a dielectric and dielectric covered with a thin metal layer. Let us consider a dielectric slab the width of which is a half of wavelength in dielectric

\[ d = \frac{\lambda d}{2} = \frac{\lambda}{2\sqrt{\varepsilon}} n \]

\[ n = 1, 2, \ldots \]

**SE minimums:**

\[ d = 0.5\lambda_d, \lambda_d, 1.5\lambda_d, \ldots \]

• Destructive interference of waves reflected from the first and second interfaces cancels total reflection from the dielectric slab
F-P anti-resonance in metalized dielectric

- Half wavelength dielectric slab with a thin metal layer on the second interface

\[ d = 0.5\lambda_d, \lambda_d, 1.5\lambda_d, ... \]

- Constructive interference of waves reflected from the first and second interfaces enhances total reflection from the metalized dielectric slab
F-P anti-resonance in dielectric slab

- Dielectric slab the width of which is \( \frac{1}{4} \) of wavelength in dielectric.

\[
d = \frac{\lambda_d}{4} = \frac{\lambda}{4\sqrt{\varepsilon}} (2n - 1)
\]

\( n = 1, 2, ... \)

SE maximums:

\[
d = 0.25\lambda_d, 0.75\lambda_d, 1.25\lambda_d, ...
\]

- Constructive interference of waves reflected from the first and second interfaces enhances total reflection from the dielectric slab.
F-P anti-resonance in metalized dielectric

- Quarter wavelength dielectric slab with a thin metal layer on the second interface

- Destructive interference of waves reflected from the first and second interfaces cancels total reflection from the metalized dielectric slab

\[ d = 0.25\lambda_d, 0.75\lambda_d, 1.25\lambda_d, \ldots \]
Resonance and anti-resonance, summing-up

- Half wavelength width dielectric demonstrates Fabry-Perot resonance: cancelling reflection – decreasing shielding effectiveness.
- Quarter wavelength width dielectric demonstrates Fabry-Perot anti-resonance: enhancing reflection – increasing shielding effectiveness.
- Metallization deposited on the second interface changes FP resonance into anti-resonance and vice versa.
- The period of Fabry-Perot resonance and anti-resonance is a half wavelength in dielectric.

\[ d = 0.5\lambda_d, \lambda_d, 1.5\lambda_d, ... \quad d = 0.25\lambda_d, 0.75\lambda_d, 1.25\lambda_d, ... \]
Single glass, $d = 4$ mm

Measurement results – points, calculation – lines for single glass without metallization, triangles, and for growing surface conductivity of metallization, circles $\sigma = 0.005$ S, squares $\sigma = 0.065$ S, stars $\sigma = 0.18$ S. $\sigma$ values were obtained by fitting calculated values with measurement results, $\varepsilon = 6.5$.

Change of F-P resonance into F-P anti-resonance when increasing $\sigma$. 
Single glass, $d = 6$ mm

Measurement results – points, calculation – lines. Lower line calculation for non-metalized 6 mm thickness glass. For the measured sample F-P resonance is changed by F-P anti-resonance and vice versa. Maximum SE up to 40 dB.
Double-glazed low-E windows

Cross-sectional view of double-glazed low-E window

Double-glazed window nomenclature $d_1m-d(Ar)-d_2$

<table>
<thead>
<tr>
<th>MANUFACTURERS NAME</th>
<th>Thickness, mm</th>
<th>Visible light transmittance</th>
<th>$\sigma$, S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climalit</td>
<td>4-15(air)-4</td>
<td>83%</td>
<td>0.0</td>
</tr>
<tr>
<td>Climaplus Relax</td>
<td>4m-16(Ar)-4</td>
<td>70%</td>
<td>0.4</td>
</tr>
<tr>
<td>Cool-Lite SKN</td>
<td>6m-16(Ar)-4</td>
<td>40%</td>
<td>0.5</td>
</tr>
<tr>
<td>Cool-Lite Xtreme</td>
<td>6m-16(Ar)-4</td>
<td>60%</td>
<td>0.6</td>
</tr>
</tbody>
</table>

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Climalit composed of two uncoated glasses demonstrates the smallest SE. All tested windows demonstrate significant decrease of SE at 9 GHz. The largest decrease is measured for Climaplus Relax (18 dB). Comparing results for windows without and with metallized glass all minima except the minima at 9 GHz are shifted to a lower frequency. Maximum SE of double-glazed windows with one metalized glass is roughly 40 dB. Calculated dependencies fit well measured. We did not find any correlation between visible light transmittance and SE.
Triple-glazed E-saving windows

Cross-sectional view of triple-glazed low-E window

Triple-glazed window nomenclature
$$d_1 m - d_{g1}(Ar) - d_2 - d_{g2}(Ar) - m d_3$$

<table>
<thead>
<tr>
<th>MANUFACTURERS NAME</th>
<th>Dimensions, mm</th>
<th>Visible light transmittance</th>
<th>$\sigma$, $S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climalit</td>
<td>4-15(air)-4-15(air)-4</td>
<td>75%</td>
<td>0.0</td>
</tr>
<tr>
<td>Climatop</td>
<td>4m-15(Ar)-4-15(Ar)-4</td>
<td>58%</td>
<td>0.18</td>
</tr>
<tr>
<td>Climatop Max</td>
<td>4m-8(Air)-4-8(Air)-m4</td>
<td>60%</td>
<td>0.18</td>
</tr>
<tr>
<td>Climatop Lux</td>
<td>4m-12(Air)-4-12(Air)-m4</td>
<td>62%</td>
<td>0.18</td>
</tr>
</tbody>
</table>
SE for Climalit composed of three uncoated glasses increases up to 20 dB. One metallized glass (Climatop) increases SE up to 40 dB. SE for this window lies between 20 and 40 dB. When two metalized glasses are used, SE increase up to 60 dB. Our setup allows to measure such SE values in frequency range 8-20 GHz. Measurement threshold is shown by red solid line. Windows with two coated glasses demonstrate a few narrower minima in comparison with double-glazed windows with one metalized glass. There is no correlation between visible light transmittance and $\sigma$. 
Summary on SE of low-E glasses and windows

- Shielding effectiveness of single low-E glass up to 30 dB, double-glazed window up to 40 dB and triple-glazed window up to 60 dB were measured.
- Such high values of SE may result in strong attenuation of GSM mobile phones, GPS and Wi-Fi signals.
- In order to improve the transmission of these useful signals it was proposed to use so called frequency selective surfaces (FSS) by etching geometrical figures in the metallization, those manifest itself as a band pass filter in the desirable frequency band.
FSS example

Periodically arranged etched crosses


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Since the window is a resonant system, our idea is to change the thickness of glasses and the gap between them and in this way to get the maximum or minimum of the transmittance at the desirable frequency range.

We investigated double-glazed low-E window with one metalized interface.

To solve optimization problem we introduce dimensionless coordinates

\[ t = \frac{d\sqrt{\varepsilon}}{\lambda} \]

optical path length

Parameter \( t \) shows how many wavelengths fit in an optical path length of particular glass or air gap.
In the case of dielectric slab $t_2 = 0.5, 1, 1.5, ...$ corresponds to SE minimum (F-P resonance), whereas $t_2 = 0.25, 0.75, 1.25, ...$ corresponds to SE maximum (F-P anti-resonance).
First we investigated double-glazed window assuming that the thickness of the first glass is zero but the metallization is at the distance $d$ (dimensionless $t$) from the second glass, $\sigma = 0.094 \, \text{S}$, $\varepsilon = 6.5$.

$$t_1 = 0, \quad t = \frac{d}{\lambda}, \quad t_2 = \frac{d_2 \sqrt{\varepsilon}}{\lambda}$$
Contour plot of dependence of $SE$ on dimensionless gap size $t$ and thickness of the second glass $t_2$ on a fixed frequency. It should be noted that calculation results are independent of frequency because both coordinates are normalized to the wavelength. Therefore the graph will be the same for any frequency. It is seen that $SE$ is periodic function on both coordinates $t$ and $t_2$ and the period is 0.5 that corresponds to the period of F-P resonance.

Now we fix $t_2 = 0.25$, and calculate the dependence of $SE$ on dimensionless thickness of the first glass $t_1$ for $t = 0.25$ and $t = 0.5$ where the maximum of $SE$ and its minimum are observed.

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It is interesting to note that in both cases the total optical path length of the window is the same. The maximum of SE is obtained when the thickness of the metalized glass is doubled in comparison with the glass in the window demonstrating the minimum of SE, whereas the air gap between glasses should be two times decreased.

It is seen that for $t = 0.25$, we are getting maximum of $SE$ when $t_1 = 0$, or 0.5, whereas for $t = 0.5$, the minimum of SE appears at $t_1 = 0.25$. It is seen that these two dependences are also periodic with period 0.5. for considered value of $\sigma$ we get the minimum of $SE = 11.4$ dB for dimensionless window $0.25m$-$0.5$-$0.25$ and the maximum of $SE = 33.4$ dB for window $0.5m$-$0.25$-$0.25$. 
Having in mind that all dependences of SE on dimensionless thickness of glasses and air gap are periodic functions with period 0.5, we can formulate generalized condition of minimum of SE

\[ t_1 = 0.25 + 0.5i, \quad t = 0.5j, \quad t_2 = 0.25 + 0.5k, \]

where \( i, j \) and \( k \) are any integer positive number starting from zero.

General SE maximum condition reads

\[ t_1 = 0.5i, \quad t = 0.25 + 0.5j, \quad t_2 = 0.25 + 0.5k. \]

As in previous case \( i, j \) and \( k \) are any integer positive number starting from zero.
Dependence on surface conductivity

In the absence of metallization $\sigma = 0$, optical path length of both windows is equal and corresponds to one wavelength leading to SE minimum (F-P resonance). It is seen that in symmetric structure (left) SE minimum is deeper in comparison with non-symmetric structure (right). When metallization is added the minimum of SE maintains its shape (left), whereas on the right figure it transforms to maximum. The similar behavior was pointed out earlier when considering influence of metallization on F-P resonance.
Dependencies of maximum and minimum values of SE versus $\sigma$. Yellow line shows dependence of the difference between maximum and minimum values of SE on surface conductivity.

- It is seen that by changing the thickness of the first glass and air gap one can get the difference of SE on the order of 24 dB.
Experimental verification

Two different home made windows were investigated experimentally. Their dimensionless nomenclature are $0.25m-0.5-0.25$ ($i=0$, $j=1$, $k=0$) and $0.5m-0.75-0.25$ ($i=0$, $j=1$, $k=0$). Measured values of $SE$ well coincide with calculated. Minimum and maximum of $SE$ appear at 7.3 GHz.
Optimization of windows at Wi-Fi frequency

Conversion of dimensionless size into mm for 2.4 and 5 GHz

<table>
<thead>
<tr>
<th>Dimensionless size</th>
<th>Thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f = 2.4$ GHz</td>
</tr>
<tr>
<td>glass 0.25</td>
<td>12.2</td>
</tr>
<tr>
<td>glass 0.5</td>
<td>24.4</td>
</tr>
<tr>
<td>air 0.25</td>
<td>31.2</td>
</tr>
<tr>
<td>air 0.5</td>
<td>62.5</td>
</tr>
</tbody>
</table>

It is seen that some dimensions of thickness of glasses and width of air gaps are not acceptable from practical point of view. Therefore we put on some restrictions on the thickness of the glass, namely 3...12 mm, and on the width of air gap, namely 10...30 mm. The lower limit of the gap accounts for the fact that at a smaller gap the thermal insulation of windows becomes too poor. On the other hand, by increasing the gap above 30 mm the window becomes too bulky, to get desirable stiffness of the frame of the window.
Dashed blue and solid green lines show constrains on $t$ and $t_2$ at 2.4 and 5 GHz, respectively. Corresponding color triangles and circles show possible minimum and maximum values of $SE$ accounting for the formulated constrains.

The change of $SE$ up to 22 dB can be obtained by changing thickness of glass and the width of the gap.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$SE_{\text{maximum}}$</th>
<th>$SE_{\text{minimum}}$</th>
<th>$\Delta SE$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4 GHz</td>
<td>3m-30-12 32.8 dB</td>
<td>12m-10-4.8 14.3 dB</td>
<td>18.5 dB</td>
</tr>
<tr>
<td>5.0 GHz</td>
<td>11.8m-15-5.9 33.4 dB</td>
<td>5.9m-30-5.9 11.4 dB</td>
<td>22 dB</td>
</tr>
</tbody>
</table>
Conclusions

• We considered resonance phenomena in a system of two dielectrics, one of which is covered with a thin metal layer and found conditions at which Fabry-Perot type resonances can be excited.
• This allows us to determine the optimal inner dimensions of low-E window providing minimum/maximum value of SE.
• Calculation results have been confirmed by experimental investigation, home made window was manufactured providing minimum and maximum SE at $f = 7.3$ GHz.
• Obtained figures of the change of the SE are on the same order of those obtained using the frequency selective surfaces of the metalized glasses.
• It seems that the variation of the longitudinal dimensions is a prospective method for the reduction/augmentation of SE.
Thank you for attention!
Higher resonances

\[ t_1 = 0.25 + 0.5i, t = 0.5j, t_2 = 0.25 + 0.5k \]

\[ i = 0, j = 1, k = 0, \quad 0.25m-0.5-0.25 \]
\[ i = 1, j = 3, k = 1, \quad 0.75m-1.5-0.75 \]
\[ i = 2, j = 5, k = 2, \quad 1.25m-2.5-1.25 \]

Thank you for attention!

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