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Inductive cross shaped metal meshes on silicon substrate

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Abstract

Thin inductive metal meshes on silicon substrate have been studied in the infrared spectral region. The wavelength-dependent transmissions of meshes with cross shaped, square shaped, rectangular shaped openings, and meshes with grating pattern were measured. The resonance wavelength and width of resonance were determined for various geometries of the openings. The Micro-Stripes program was used for the calculation of resonance wavelength and width of resonance of cross shaped metal meshes and best-fit formulas were developed for the presentation of the data. The dependence on the shape of the opening was studied for free standing thin meshes and meshes on a silicon substrate. The Wood anomaly was studied experimentally for cross, square, rectangular shaped meshes and for gratings on silicon substrate. A simple model for the dependence of the Wood anomaly on the refractive index is presented.

1. Introduction

In an earlier paper [1] we have investigated the infrared transmittance of thin cross shaped inductive and capacitive metal meshes on thick (500 μm) silicon substrate. It was found that the measured and calculated resonance wavelength of a mesh deposited on a silicon substrate was shifted to longer wavelength in comparison to a free standing mesh. The resonance wavelength shifted only by a factor of 2.87, an amount smaller than the refractive index 3.4 of silicon.

In this paper we report on inductive metal meshes deposited on silicon substrates with various shapes of the openings, and use the Micro-Stripes simulation program [2] for the calculation of the transmittance of free standing meshes and meshes on silicon substrate. There is a very good agreement of the experimental data with the calculations using the Micro-Stripes program, and we consider the results of the simulations equivalent to experiments.

In Fig. 1 we show the geometrical parameters of inductive metal meshes. The cross shaped meshes have the shape parameters g, $2a$ and $2b$, square shaped meshes have g and $2a$ and rectangular meshes g, $2a$ and $2c$. The grating has a periodicity

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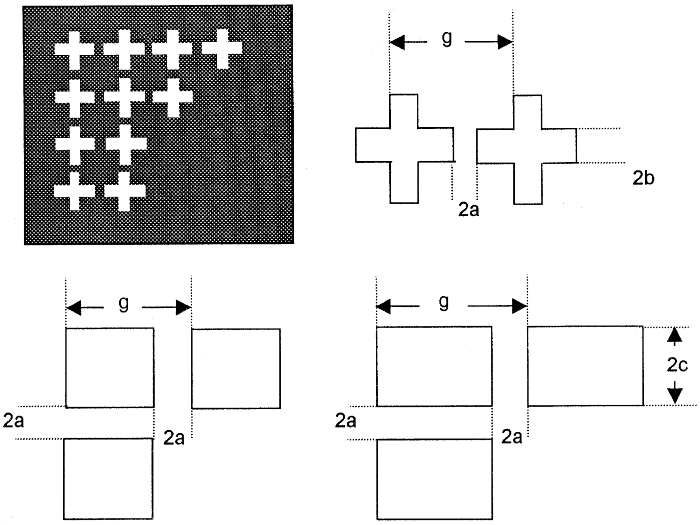

Fig. 1. Geometrical parameters of inductive metal meshes. (a) Cross shaped metal mesh with periodicity constant g, separation $2a$ and width of cross arms $2b$. (b) Inductive square shaped mesh with periodicity constant g and separation $2a$. (c) Rectangular shaped mesh with periodicity constant g, separation $2a$, and rectangular width $2c$. (d) Grating shaped mesh with periodicity constant, and separation $2a$.

constant g and openings of width $g/2$. The metal thickness of all meshes is $t = 0.2$ μm.

The Micro-Stripes program was used to calculate the dependence of the transmittance on the shape parameters a and b of meshes with cross shaped openings, free standing and on a silicon substrate. The calculated data of resonance wavelength λ_R and width of the resonance WR ($\Delta\lambda/\lambda$) are presented by non-linear relations.

Meshes with cross, square and rectangular shaped openings, and gratings were deposited on silicon wafers of thickness of 500 μm and the experimental values of resonance wavelength and width of resonance were determined from the transmittance data and compared to simulated data.

In the previous paper [1] we found that the Wood anomaly was shifted by the value of 3.4 of the refractive index of silicon, compared to a free standing mesh. The Wood anomaly has been investigated experimentally for different mesh geometries and shape parameters. A simple model for the Wood anomaly is presented and the dependence of the shift on the refractive index calculated.

2. The Micro-Stripes program

The Micro-Stripes program [2] provides 3D electromagnetic analysis of arbitrary geometries, yielding results in time/frequency domain and uses the transmission line method (TLM). This method is based on establishing a network of transmission lines that represents the physics of the problem, and finding equivalence between the electrical solutions of that network and the physical parameters of the problem.

In order to construct the computational mesh, a workspace needs to be defined, followed by the construction of the mesh. Each mesh is actually defined by a small rectangular homogenized cell. Each cell is entirely empty or entirely filled with the same metal or dielectric. The greater the number of cells, the greater the accuracy in defining the geometry of the device and the longer the calculation time.

The input data are the geometrical parameters, boundary conditions, surface impedance of the metal and resistivity of the dielectric. The surface impedance of a free standing copper mesh was determined by calculation of the transmittance of a thick cross shaped metal mesh with geometrical parameters $g = 20$ μm, $2a = 1.5$ μm, $2b = 3$ μm, produced by Ruprecht et al. [3] using the LIGA method. The calculated intensity agreed very well when using for the calculations a surface impedance of $Z = 1.635$ Ω cm while all wavelengths of the peaks were reproduced within a few percent. Ruprecht et al. [3] report about the same transmittance for copper and nickel meshes with the same geometrical parameters while the bulk value of the resistivity is quite different. The geometrical parameters and the value of the surface impedance of 1.635 Ω cm have been used successfully in the study of one, two and four free standing metal meshes.

A different value of $Z = 1$ Ω cm was chosen for aluminum metal meshes on silicon substrates. The observed transmittances were very well reproduced using this values of Z for a number of aluminum meshes on silicon substrate with different pattern and geometrical parameters, see Ref. [1] and Fig. 8.

3. Free standing cross shaped metal meshes

Chase and Josef [7] have investigated the transmittance of six types of cross shaped meshes with shape parameters of a/g between 0.05 and 0.2 and b/g between 0.56 and 0.15 and gave empirical formulas for resonance wavelength and width of resonance.

We have used the Micro-Stripes program to calculate the resonance wavelength λ_R and width of resonance WR for 25 sets of g, a, and b.

In Fig. 2 we have plotted the resonance wavelength λ_R, calculated for $g = 20$ μm, $2a = 3, 4, 6, 8, 9$ μm and $2b = 2, 4, 5, 6, 7$ μm. The resonance wavelength λ_R is plotted depending on a and b. The Micro-Stripes data have been presented by a non-linear best-fit formula

$$\lambda_R = 0.2933a^2 - 0.0032b^2 + 0.657ab - 6.2444a - 4.3527b + 2.4539g \quad (1)$$

with a standard deviation of 0.2 μm.

The Micro-Stripes program was also used to calculate the width of the resonance (WR) defined as width at half height ($\Delta\lambda/\lambda$). In Fig. 3 we show WR for $g = 20$ depending on a/g and b/g. We have chosen $b/g = 0.05, 0.1, 0.125, 0.15, 0.175$ and calculated the resonance wavelength depending on $a/g = 0.075, 0.1, 0.15, 0.2, 0.225$ for each of these values.

The results of the calculations have been presented with a non-linear best-fit formula

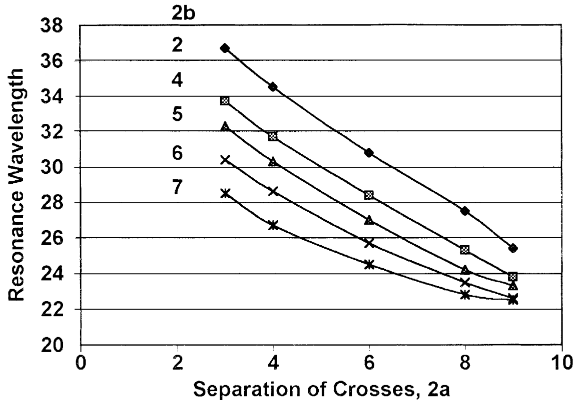

Fig. 2. Micro-Stripes calculations of the resonance wavelength of free standing inductive cross shaped metal mesh of thickness 0.2 μm and using a surface impedance $Z = 1.635$ Ω cm. The dependence on the separation of the crosses and the width of the cross arms is shown for the range of $a/g = 0.075$, 0.1, 0.15, 0.2, 0.225 and $b/g = 0.05$, 0.1, 0.125, 0.15 and 0.175.

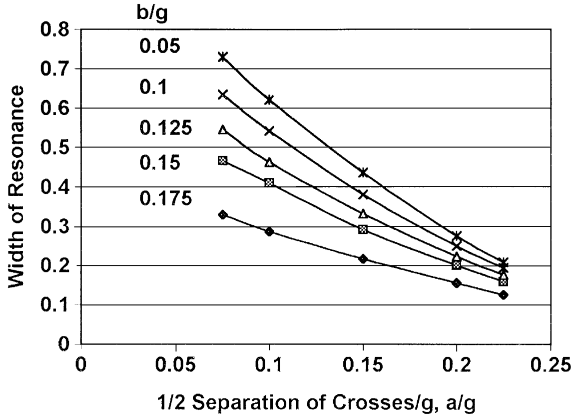

Fig. 3. Micro-Stripes calculations of width of resonance ($\Delta\lambda/\lambda$) of free standing inductive cross shaped metal mesh of thickness 0.2 μm and using a surface impedance $Z = 1.635$ Ω cm. The dependence on the separation of the crosses and the width of the cross arms is shown for the range of $a/g = 0.075$, 0.1, 0.15, 0.2, 0.225 and $b/g = 0.054$, 0.1, 0.125, 0.15 and 0.175.

$$\Delta\lambda/\lambda = -2.441(a/g)^2 - 2.7827(b/g)^2 - 21.7103(a/g)(b/g) + 0.9677(a/g) + 0.58824(b/g) \quad (2)$$

and the standard deviation was obtained as 0.023.

4. Cross shaped metal meshes on silicon substrate

When a mesh is deposited on a dielectric substrate or embedded in it, the resonance wavelength shifts to a longer wavelength [8]. We have used the simulation program and studied the shift of the resonance wavelength depending on the thickness of a dielectric layer on one or both sides of the mesh, see Ref. [5]. The resonance wavelength λ_R shifts to a longer wavelength by a factor equal to the refractive index n when embedded in a thick dielectric layer; however, on a substrate the shift is less than n. This has been observed experimentally [1] by comparing the resonance wavelength of the mesh on a silicon substrate and a free standing mesh.

Ulrich [9] has presented a mode analysis of free standing metal meshes and we have extended the model to modes of a metal mesh on a dielectric substrate [4,5]; see a schematic presentation in Fig. 4. The incident light induces surface waves on both sides of the mesh, a mode is formed and the mode transfers the incident light into the reflected and transmitted light. A free standing mesh has both surface waves oscillate in air, while for a mesh on a substrate one of the surface waves oscillates in the dielectric. The oscillation of the surface wave in the dielectric affects the resonance wavelength of the mode and shifts it to a longer wavelength by an amount less than the refractive index n.

In Ref. [1] we have compared the experimental shift of the wavelength with the resonance wavelength λ_R obtained from an empirical formula for free standing meshes. The simulation program was used to calculate the resonance wavelength λ_R and width of resonance WR for a mesh on a silicon wafer of thickness of 550 μm and resistivity of 15 Ω cm. In Section 5 we will compare the results for the free standing mesh and the meshes on a silicon substrate and plot their dependence on the shape parameters a and b.

The simulation program was applied to the calculations of the resonance wavelength λ_R and width of resonance WR for meshes with $g = 20$ μm and $2a = 3, 4, 6, 8, 9$ μm and $2b = 2, 4, 5, 6, 7$ μm. In Fig. 5 the resonance wavelength λ_R is plotted depending on a/g and taking b/g as parameter.

The calculated data of the resonance wavelength are presented by a non-linear best-fit formula

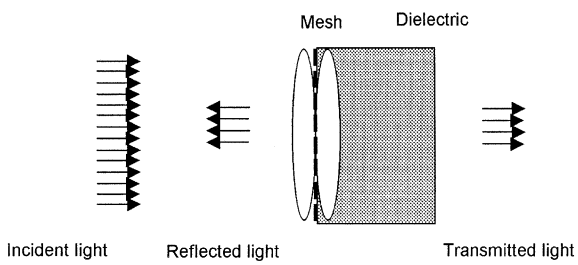

Fig. 4. Schematic of interaction of incident light with a metal mesh. The incident light excites standing surface waves on both sides of the mesh, shown in white. The surface waves form a resonance mode of the mesh. If one surface wave oscillates in a dielectric the wavelength of the resonance mode shifts to longer wavelength. The mode transfers the energy of the incident light to the reflected and transmitted light.

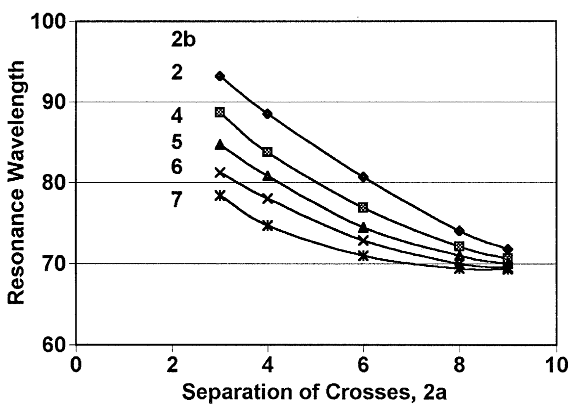

Fig. 5. Micro-Stripes calculations of the resonance wavelength of an inductive cross shaped metal mesh of thickness 0.2 μm and surface impedance of $Z = 1.635$ Ω cm. The mesh was assumed to be on a silicon substrate of thickness of 550 μm and surface resistance of 15 Ω cm. The dependence on the separation of the crosses and the width of the cross arms is shown for the range of $a/g = 0.075, 0.1, 0.15, 0.2, 0.225$ and $b/g = 0.05, 0.1, 0.125, 0.15$ and 0.175.

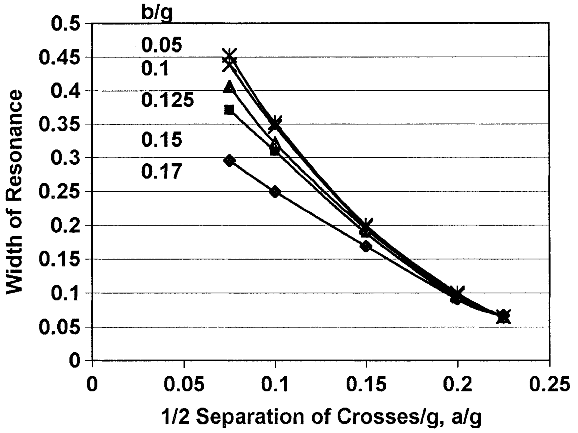

Fig. 6. Micro-Stripes calculations of the width of resonance ($\Delta\lambda/\lambda$) of an inductive cross shaped metal mesh of thickness 0.2 μm and surface impedance of $Z = 1.635\ \Omega$cm. The mesh was assumed to be on a silicon substrate of thickness of 550 μm and surface resistance of 15 Ω cm. The dependence on the separation of the crosses and the width of the cross arms is shown for the range of $a/g = 0.075$, 0.1, 0.15, 0.2, 0.225 and $b/g = 0.05$, 0.1, 0.125, 0.15 and 0.175.

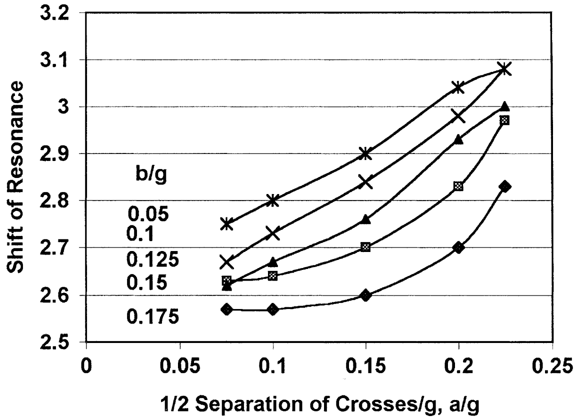

Fig. 7. Shift of the resonance wavelength of the free standing mesh when deposited on the silicon substrate. The resonance wavelength, calculated for the mesh on the silicon substrate, is divided by the resonance wavelength calculated for the free standing cross shaped mesh. The dependence on the separation of the crosses and the width of the cross arms is shown for the range of $a/g = 0.075$, 0.1, 0.15, 0.2, 0.225 and $b/g = 0.05$, 0.1, 0.125, 0.15 and 0.175.

$$\lambda_R = 1.1475a^2 - 0.1146b^2 + 1.7115ab - 15.9656a - 8.3165b + 6.0544g \quad (3)$$

with a standard deviation of 0.323.

In Fig. 6 we show the WR for $g = 20$ depending on a/g and b/g. We have calculated a best-fit formula for the width of resonance WR defined as width at half height divided by the peak wavelength ($\Delta\lambda/\lambda$)

$$\Delta\lambda/\lambda = -4.34(a/g)^2 - 10.21(b/g)^2 - 17.98(a/g)(b/g) + 1.09(a/g) + 5.31(b/g) \quad (4)$$

with a standard deviation of 0.075.

5. Shift of resonance wavelength on silicon

In Ref. [1] we reported that the resonance wavelength of a free standing cross shaped mesh shifts on the average by a factor of 2.78 compared to the mesh deposited on silicon substrate. We will now obtain the dependence of this factor on a/g and b/g values. In Fig. 7 we have plotted the ratio of the calculated resonance wavelengths of the cross shaped meshes on silicon substrate (Fig. 5) divided by the resonance wavelength of the free standing mesh as shown in (Fig. 3).

An empirical best-fit formula was obtained for the presentation of the calculated data.

$$2.257(a/g) + 2.051(b/g) + 0.9[(n_1^2 + n_2^2)/2]^{1/2} \quad (5)$$

Whitbourn and Compton [8] have used transmission line theory to study the shift of the wavelength of a metal mesh on a thick dielectric substrate and arrived at a shift factor of $[(n_1^2 + n_2^2)/2]^{1/2}$, where n_1 is the refractive index of the dielectric on the front side of the mesh and n_2 on the back side. For $n_1 = 1$ and $n_2 = 3.4$ the value of $[(n_1^2 + n_2^2)/2]^{1/2}$ is 2.5. We have arranged the best-fit formula of Eq. (5) in such a way that the terms depending on a/g and b/g appear as correction terms to the result of Ref. [8]. An interpretation may be given in terms of the mode model, see Fig. 4. A mode corresponding to the resonance wavelength is composed of two strongly coupled surface waves. When one surface wave oscillates in a dielectric, the wavelength of the mode shifts to longer wavelength. The coupling of the two surface waves seems to depend on the geometry of the crosses. The shift factor gets larger with larger a/g values, that is with larger separation of the crosses, and smaller with larger b/g values, that is larger values of the width of the cross arms.

6. Comparison with experiments

6.1. Resonance wavelength

We have produced cross shaped metal meshes with $g = 20$ μm, $2a = 8$ μm, and $2b = 6$ μm of aluminum of thickness $t = 0.2$ μm on a silicon wafer of thickness of 550 μm with resistivity of 15 Ω cm. The experimental transmittance shows a peak wavelength of 71.3 μm while the calculations resulted in a peak wavelength of 70.2 μm; see Fig. 8. There is good agreement of the overall intensity, confirming the validity of the used surface impedance values for the metal and the conductivity value for the dielectric.

6.2. Width of resonance

The experimentally observed width of resonance, $\Delta\lambda/\lambda$, of cross shaped meshes with different geometries is compiled in Table 1. The experimental data are in very good agreement with the calculations and the results of the best-fit formulas.

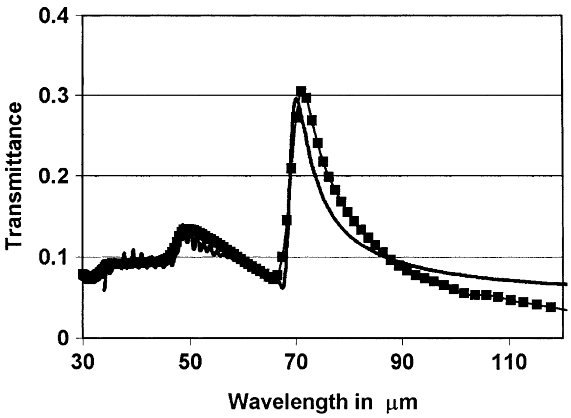

Fig. 8. Transmittance of inductive cross shaped metal mesh of thickness 0.2 μm on a silicon substrate of thickness of 550 μm depending on the wavelength. The grid has geometrical parameters $g = 20$, $2a = 8$, $2b = 6$ μm: (a) measured resonance wavelength at 71.3 μm, (b) simulation wavelength at 70.2 μm.

Table 1
Experimental and calculated width of resonance $\Delta\lambda/\lambda$

	Experimental	WR formula	Micro-Stripes
Cross g = 26.4 $2a = 3.2$, $2b = 4.8$ $a/g = 0.06$, $b/g = 0.09$	0.3472	0.347	0.3683
Cross g = 16.4 $2a = 2.5$, $2b = 4.8$ $a/g = 0.0762$, $b/g = 0.0146$	0.39	0.416	0.41667
Cross g = 20 $2a = 2.4$, $2b = 3.6$ $a/g = 0.06$, $b/g = 0.09$	0.3253	0.347	0.37
Cross g = 20 $2a = 8$, $2b = 6$ $a/g = 0.2$, $b/g = 0.15$	0.101	0.07	0.097
Cross g = 12.5 $2a = 1.5$, $2b = 2.25$ $a/g = 0.06$, $b/g = 0.09$	0.3406	0.347	0.344

7. Meshes with square shaped openings

Inductive square shaped meshes with $g = 20$ μm and $2a = 64$, 8, 10 μm were produced on a silicon substrate. The meshes were made of aluminum on a silicon substrate of thickness 550 μm and resistivity of 15 Ω cm. The transmittance is shown in Fig. 9 and the resonance wavelength of two of the square meshes of $2a$ equal 6 and 8 μm is at 70.07 μm, the third with $2a = 10$ μm at 71.03 μm. The peak transmittance increases at smaller separation. Around 50 μm one observe a resonance exactly at $2.5g$, with $g = 20$ μm.

8. Wood anomaly

In our previous paper [1] we reported on the minima of transmittance at a wavelength close to the periodicity for several cross shaped metal meshes on a thick silicon substrate.

The meshes had different periodicity constants g and the refractive index of silicon was assumed to

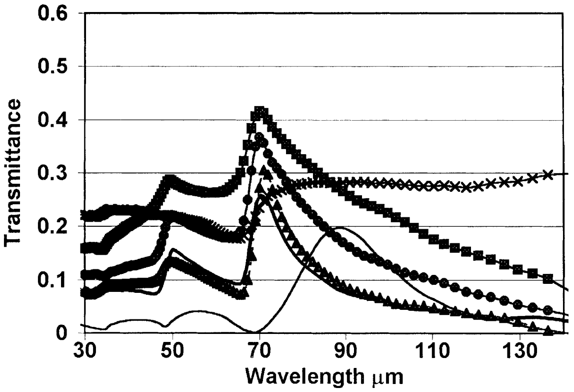

Fig. 9. Transmittance depending of wavelength of experimental measurements thin metal meshes on silicon substrate. Squares: square shaped inductive mesh with geometrical parameters $g = 20$ µm, $2a = 6$ µm and peak wavelength at 70.07 µm. Round dots: square shaped inductive mesh with geometrical parameters $g = 20$ µm, $2a = 8$ µm and peak wavelength at 70.07 µm. Thick solid line: square shaped inductive mesh with geometrical parameters $g = 20$ µm, $2a = 10$ µm and peak wavelength at 71.03 µm. Thin solid line: rectangular shaped inductive mesh with geometrical parameters $g = 20$ µm, $2a = 16$ µm, $2c = 16$ µm and peak wavelength at 89.4 µm. Triangle: cross shaped inductive mesh with geometrical parameters $g = 20$ µm, $2a = 8$ µm, $2b = 6$ µm and peak wavelength at 71.3 µm. x-line: grating with periodicity constant $g = 20$ µm and separation of 10 µm.

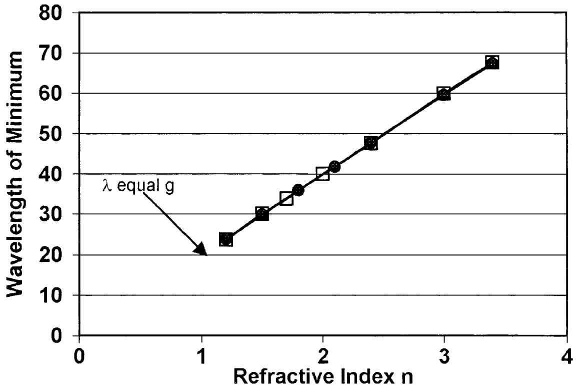

Fig. 10. Minima of Wood's anomaly depending on refractive index of substrate of thin inductive cross and square shaped meshes. Black dots: calculated minima of cross shape meshes with $g = 20$ µm, $2a = 8$ µm, $2b = 6$ µm. Squares: calculated minima of square shaped mesh with $g = 20$ µm, $2b = 6$ µm. The line points to the value of $g = 20$ µm for $n = 1$.

be 3.4. We have extended this study to different structures, all having the same periodicity constant $g = 20$ µm, and the experimentally observed minima are shown in Fig. 9. There are square shaped meshes indicated by squares, dots and thick solid lines, all having peak wavelengths around 70 µm. The thin solid line represents a rectangular shaped mesh with peak wavelength at 89.4 µm and the line with triangles a cross shaped mesh of peak wavelength 71.34 µm. The xx-line represents a grating with periodicity constant $g = 20$ and width of openings of 10 µm.

The product of $g = 20$ times $n = 3.4$ is 68 and a minimum is observed for all traces close to this value of the wavelength, assigned to the Wood anomaly.

We have used a simple model for the interpretation. At normal incidence, when the diffraction angle is larger than 90°, the diffracted light propagates as an evanescent wave in the medium of the substrate. Similar as discussed above for the modes of the metal mesh embedded in a dielectric, the wavelength of the evanescent wave is shifted by the refractive index n.

The simulation program was used to calculate the minimum wavelength λ_W for cross and square shaped pattern on substrates with various refractive indices. The dependence of λ_W on the refractive index is shown in Fig. 10. The line approaches 1 at $\lambda_W = 20$ µm, the wavelength equal to the periodicity constant.

9. Discussion

Micro-Stripes calculations were done for a specific periodicity constant $g = 20$ µm and the resonance wavelength and width of resonance were studied depending on the shape parameters a/g and b/g.

The calculations were done for the non-realistic case of free standing meshes with thickness $t = 0.2$ µm. The dependence on the separation of the crosses $2a$ and the width of the cross arms $2b$ shows that larger crosses have a resonance at longer wavelength with larger width of resonance, while smaller crosses have a resonance at shorter wavelength with smaller width of resonance, in agreement with Ref. [7]. A similar study for meshes on silicon of thickness of about 550 µm (studied in this paper) shows in comparison a large shift of the resonance wavelength with shift by a factor between 2.6 and 3.1 and a reduction of width of resonance. The intensities shown in the figures are average intensities after elimination of fringes of the silicon plate.

The results of the simulation calculations show non-linear relations and the best-fit formulas are also non-linear. Even though the resonance is displayed in terms of a non-linear relation, the relation for the resonance wavelength shows a greater contribution for the linear terms. The non-linear terms seem to take effect mainly at the limits of the investigated range of separation and widths of the cross.

The shift factor for free standing meshes when deposited on a silicon substrate depends on size and shape of the crosses. With respect to the mode model, the surface waves are coupled through the openings and therefore the coupling depends on the parameters a and b. There is no simple relationship of the shift factor depending on the open area. The shift factor increases with increases a/g while the open area decreases, and the shift factor decreases with increasing b/g values while the open area increases.

The experimental data agree very well with the results of the simulation calculations for the 0.2 μm thick cross and square shaped pattern on silicon, confirming the choice of the surface impedance $Z = 1\ \Omega\,\mathrm{cm}$ for meshes of aluminum.

The resonance wavelengths of the inductive square shaped meshes are all close to 71 μm and have decreasing peak intensity with increasing separation, that is for decreasing open areas. This may depend on the coupling, which becomes larger with smaller separation and results in higher transmittance.

In Fig. 9 one has peaks at about 50 μm, that is at 2.5 times the periodicity constant $g = 20$ μm. An interpretation may be given by considering thick metal meshes [6] which show at wavelengths shorter than the resonance wavelength series of peaks depending on the thickness of the mesh. For small thickness a narrow peak around $\lambda_R \approx g$ appears and simulation calculations show a delta function at $\lambda_R = g$. When the mesh is on a silicon substrate, the delta function may be perturbed and shows up as a broader peak. The perturbation may arise from the fact that the two surface waves on the front and back of the mesh might not have the same wavelength and therefore their coupling is different from the free standing case. As we saw above, resonance peaks of meshes on silicon substrate have shift factors from 2.6 to 3.1, and a value of 2.5 is at the lower limit.

The Wood anomaly appears for free standing meshes at $\lambda_W = g$, in agreement with experimental data of thick cross shaped and tripod shaped meshes; see Ref. [3]. The Wood anomaly is observed at a longer wavelength than g for meshes on a substrate, and removed from a value associated with singularities for many computational programs.

The numerical calculations of the Micro-Stripes program uses ratios with respect to the periodicity of the geometry; therefore we think the results are valid in a large range of the periodicity constant from the near to the far infrared.

10. Summary

The resonance wavelength and width of resonance of metal meshes with periodicity constant $g = 20$ μm on silicon substrates have been studied experimentally. The Micro-Stripes program has been applied for the investigation of meshes on silicon substrate and free standing meshes. The dependence of the resonance wavelengths and widths of resonance on the geometrical parameters has been studied for cross, square and rectangular shaped openings of meshes and for gratings. The Wood anomaly has been studied for cross and square shaped openings of meshes and gratings and a simple model for the dependence on the refractive index was presented. There is excellent agreement of the experimental data with the Micro-Stripes calculations.

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