Optical Properties of Split Ring Resonator Metamaterial Structures on Semiconductor Substrates

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ABSTRACT

Metamaterials based on single-layer metallic Split Ring Resonators (SRR) and Wires have been demonstrated to have a resonant response in the near infra-red wavelength range. The use of semiconductor substrates gives the potential for control of the resonant properties of split-ring resonator (SRR) structures by means of active changes in the carrier concentration obtained using either electrical injection or photo-excitation. We examine the influence of extended wires that are either parallel or perpendicular to the gap of the SRRs and report on an equivalent circuit model that provides an accurate method of determining the polarisation dependent resonant response for incident light perpendicular to the surface. Good agreement is obtained for the substantial shift observed in the position of the resonances when the planar metalisation is changed from gold to aluminium.

Keywords: Split ring resonators**,** Wires, equivalent circuit model, gold, aluminium

1. INTRODUCTION

Split ring resonators (SRRs) have been used extensively in investigations of metamaterial properties since their proposal and the demonstration of doubly negative behaviour by Pendry [1] and Smith [2]. However the properties of interest provided by metamaterial extend beyond the case of the doubly negative: other aspects of interest include extreme properties, together with tunability and switchability. One possible way to achieve the latter properties is the use of an active or dopeable semiconductor substrate [3,4]. Such substrates typically have a substantially higher refractive index than that of glass – which is the 'traditional' lower index substrate.

We have investigated the properties of metamaterial structures that involve a combination of SRRs and extended metal wires, mostly using substrates of single crystal silicon – and we have compared the properties of realizations based on gold with those of meta-materials based on the same configuration, and with nominally identical dimensions, but based on aluminium. The complex dielectric properties of the two metals are significantly different and the properties observed are correspondingly quite different in some, but not all, respects.

2. BASIC RESONANCES

The two principle types of resonance observable in a 'C' or 'U' shaped SRR are usually called the plasmon or Mie resonance, at shorter wavelengths, and the so called LC resonance, at longer wavelengths. The identification of the longer wavelength resonance as an LC resonance was made by Linden et al [5], with frequency of the resonance is approximately determined by considering the SRR to be a single turn inductor in series with the capacitor formed by the gap between the SRR arms. Alternative designations by Rockstuhl et al [6] have indicated that the resonances observed may be interpreted as simply being the symmetric or antisymmetric fundamental and higher order plasmon resonances.

In either case, when the ring is closed the second or LC resonance is absent in TE polarization, i.e. when there is no gap across which an electric field can be developed. It remains important to recognize that there is a significant amount of electro-magnetic energy storage in the gap region of the SRR, so that SRR structures with identical total metallic track lengths, but different gaps, do not have the same resonance frequency.

1.1 Effect of substrate

A 3-D FDTD simulation has been used to calculate the effect of changing the substrate material from glass with a refractive index of 1.5 to a potentially active silicon substrate with n= 3.1. As shown in Fig. 1 the change of substrate from glass to silicon results in an approximate 20% increase in the resonance wavelength. This change is substantially less than the change in the refractive index because part of the resonant electromagnetic distribution resides in the near-surface region of the metal film and part is in the air above the metal.

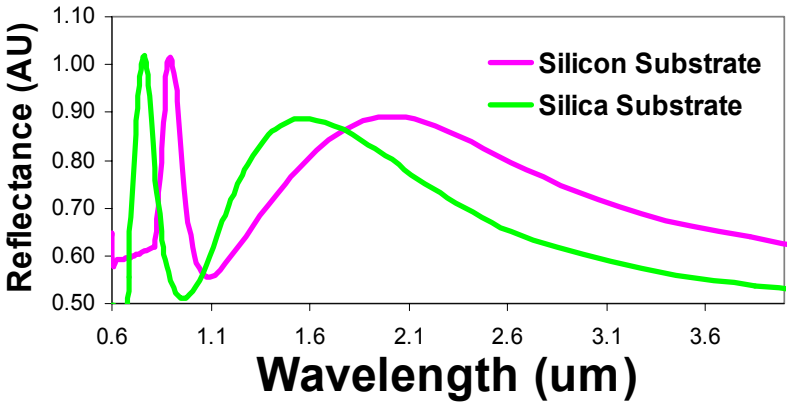

Figure1 Effect of substrate on resonance wavelength

3. EFFECT OF METAL

3.1 Larger structures

In our previous work, [7] we have shown that for moderately small sizes SRRs, i.e. ones with arm lengths of around 560 nm, leading to LC resonances at wavelengths around 8 microns, the choice of metal has no significant effect. This behaviour is illustrated in Figure 2

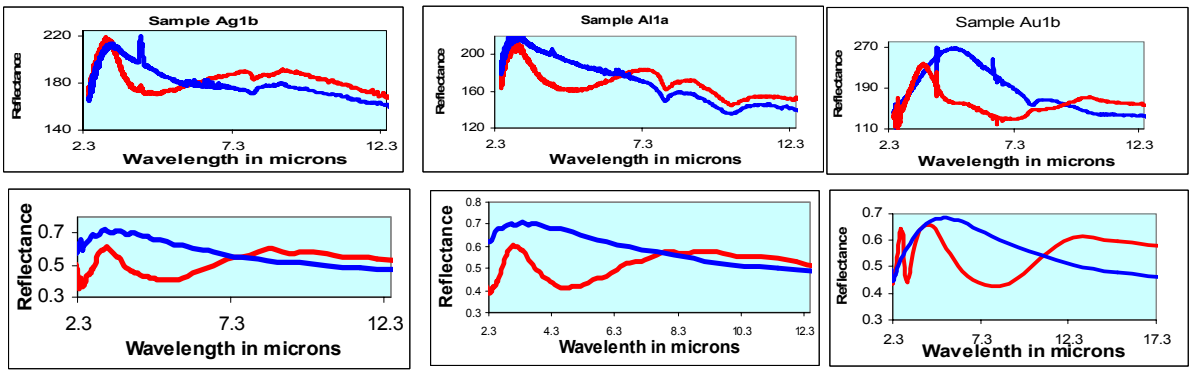

Figure 2 Reflectance spectra for various metal SRRs on silicon: top row are measurements and bottom row are simulations. Going from left to right the metals are successively silver, aluminium and gold. The blue traces are TM polarisation (electric field perpendicular to the SRR gap) and red traces TE polarisation (electric field parallel to the SRR gap).

3.2 Smaller structures

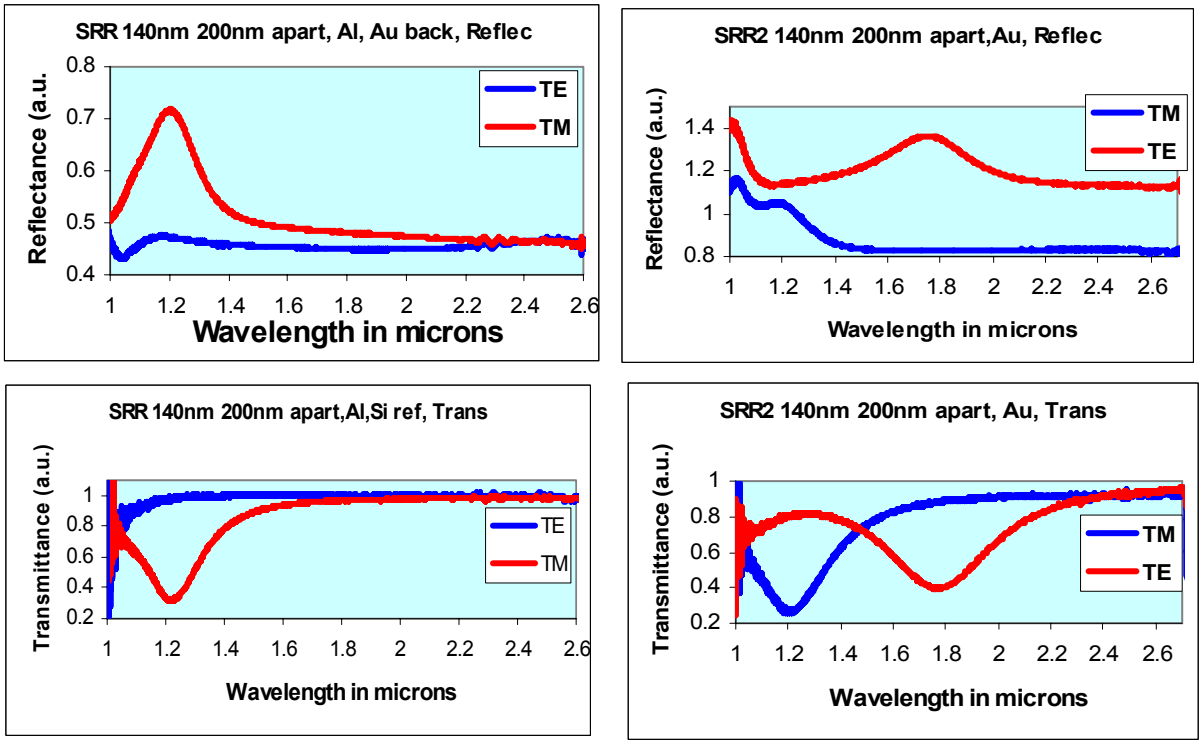

Figure 3 Reflectance and transmission spectra of aluminium (left) and gold (right)

The main differences in spectra from the previous set are a very significant blue shift in going from gold to aluminium metalisation for 200 nm gold SRRs, while the Mie resonance feature is smaller in magnitude than the LC

resonance (in TE). The Mie resonance for TE is merging with the characteristic feature of the silicon band-edge at a wavelength of 1.1 µm.

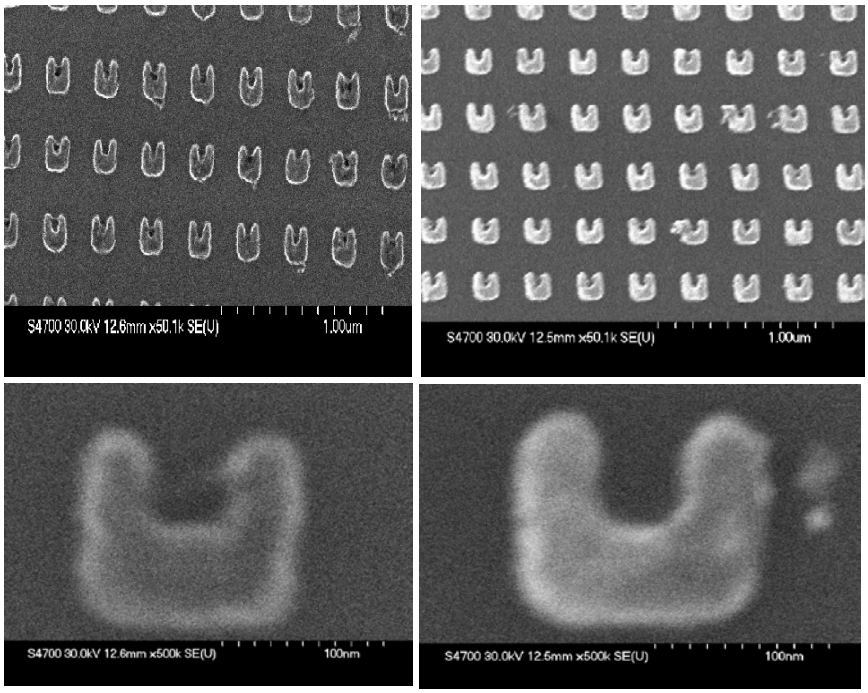

Figure 4 SEM images of SRRs fabricated in aluminium (left) and gold (right).

4. ADDITION OF WIRES

The addition to the total pattern of extended wires between rows or columns of SRRs is known to affect the detailed behaviour of the SRR resonances [8], although it is not conclusive that this addition leads to doubly negative behaviour. Here we limit ourselves to considering the influence of the presence of the extended wires on the magnitude and position of the resonances.

4.1 Wires Parallel to the gap

In TE polarisation, asymmetric broadening of the LC peak towards the blue occurs, together with an apparent strengthening in gold of the LC resonance. The TM peak remains washed out in aluminium.

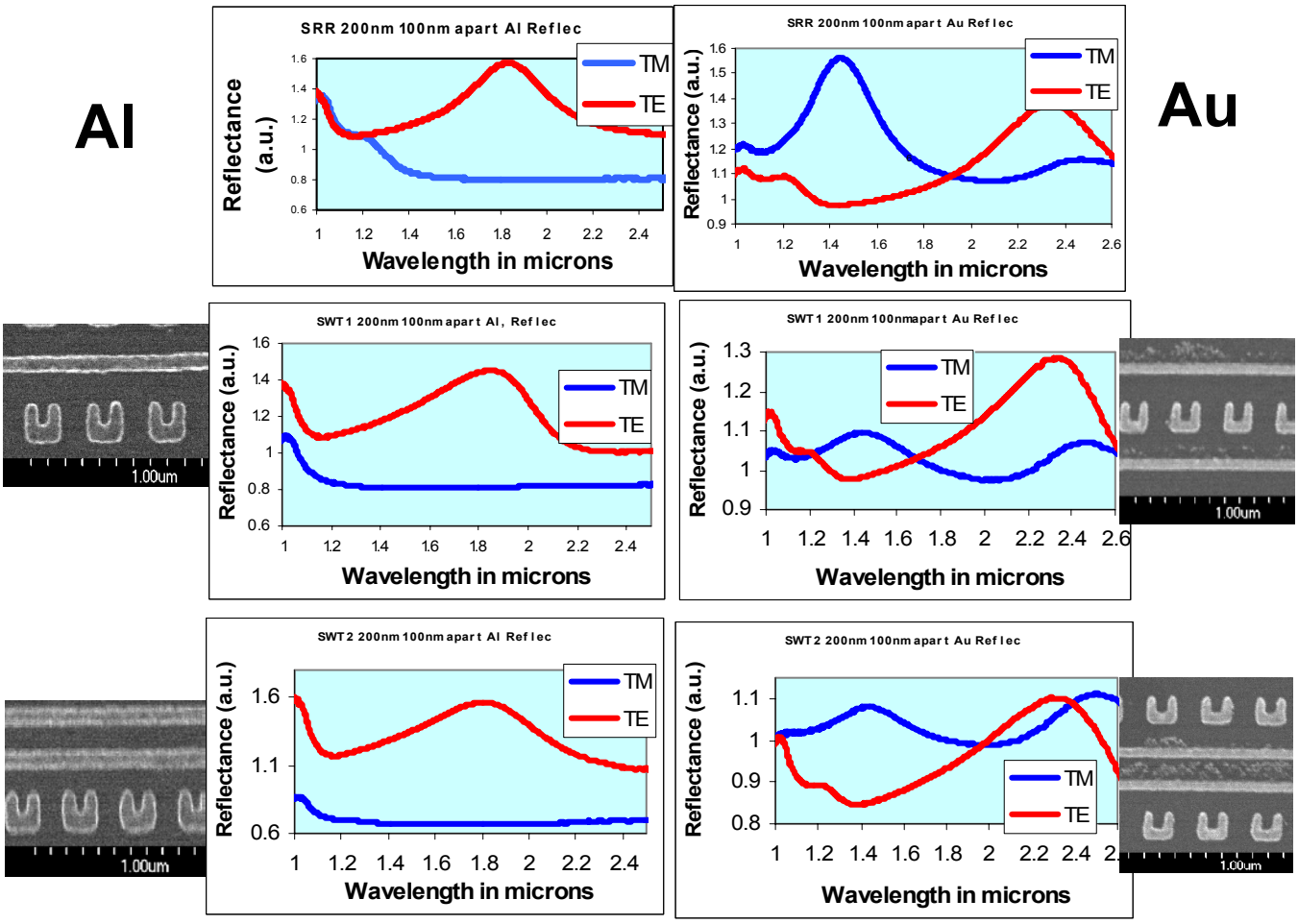

Figure 5: Reflectance spectra of aluminium and gold with wires parallel to the SRR gaps. The top row of patterns do not include wires - and are shown for comparison.

4.2 Wires Perpendicular to the SRR gaps

Suppression of the LC resonance due to the presence of the wires appears more clearly for the case of aluminium. The substrate absorption edge reflection feature at a wavelength of approximately 1.05 µm is observed in all cases. The TE Mie resonance for TE excitation is not observable in the aluminium samples because of the substrate absorption at the relevant wavelengths. The presence of the wires gives a large difference for TM excitation, with extra peak being observed only for the case of gold. The overall magnitude of the LC resonance observed depends on the orientation of the wires.

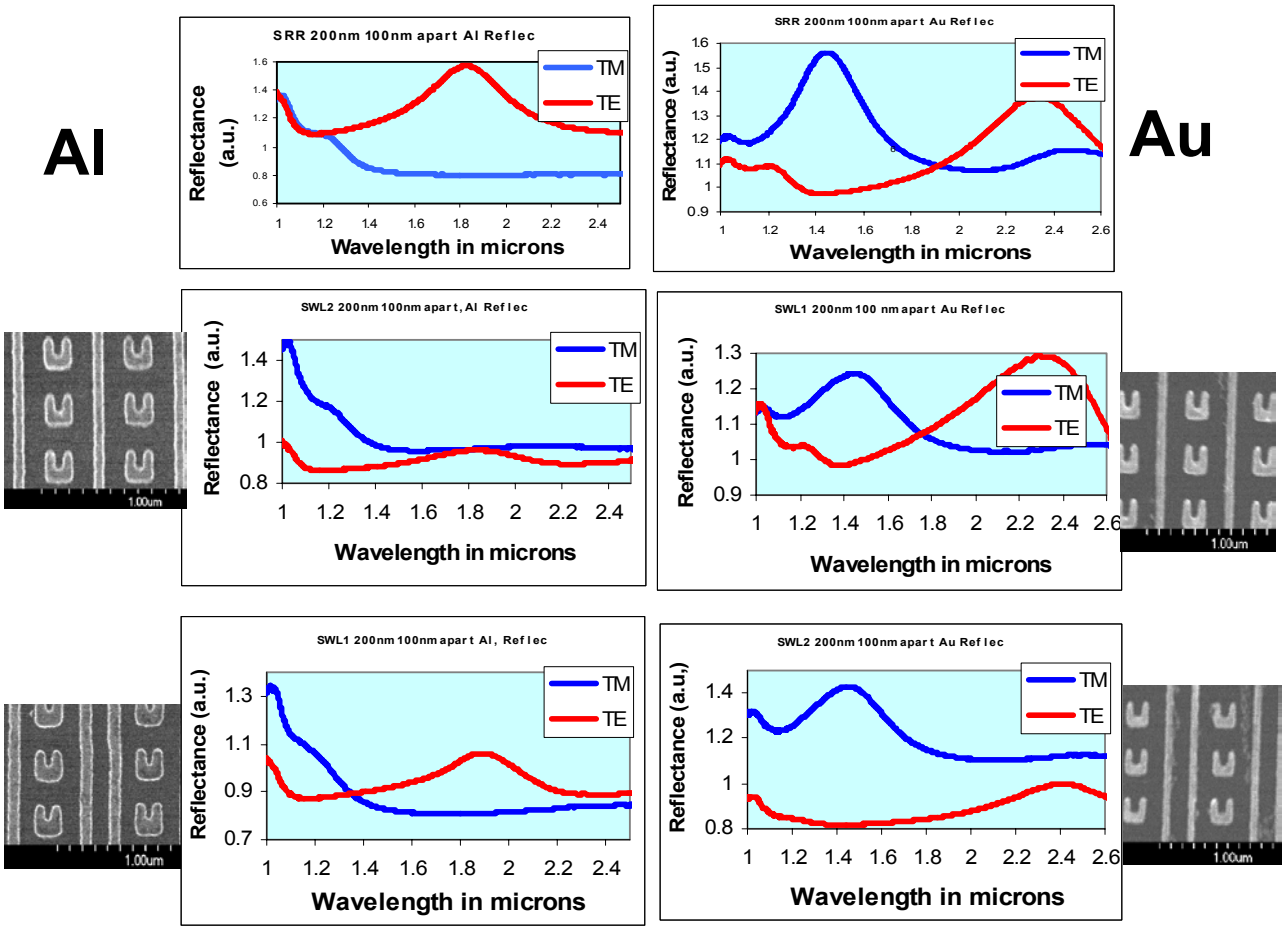

Figure 6: Reflectance spectra of aluminium and gold with wires perpendicular to the SRR gaps. The top row are for SRR patterns without wires - and are shown for comparison.

5. EXPLANATION OF DIFFERENCES OBSERVED DUE TO ALTERNATIVE CHOICES OF METALLISATION

Overall, apart from the broadening of the LC feature and the possible reduction in the LC resonance magnitude associated with aluminium, the differences between the spectra are not large. The equivalent circuit model that we have developed [7] for the SRR inductance and capacitance does not relate the actual metal properties to the behaviour of the LC resonance. However the amount of the inductance (as proposed by Tretyakov [9]) that should be added into the equivalent circuit model (and previously interpreted by Pendry [10] as being due to the additional kinetic energy associated with the motion of the electrons in the metal), will depend on the choice of metal. The higher plasma frequency of aluminium will result in a lower additional inductance - and therefore in a shorter resonance wavelength.

5.1 Model outline

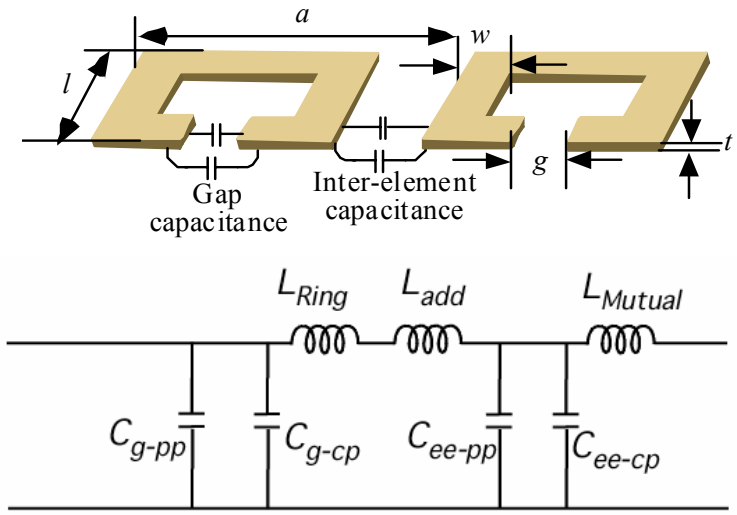

Figure 7 Equivalent circuit model showing main contributions to capacitance and inductance.

In terms of the device geometry defined in Fig. 7 the current distribution around the ring is given by:

$$I = j\omega\varepsilon_0 \frac{wt}{l}\left(1 - \frac{\omega_p^2}{\omega^2}\right)V \tag{1}$$

This could be considered in terms of additional inductance and capacitance of the SRR due to the presence of both Electric and Magnetic field inside it as.

$$I = \left(j\omega\frac{\varepsilon_0 wt}{l} + \frac{\varepsilon_0 wt\omega_p^2}{j\omega l}\right)V = \left(j\omega C_{add} + \frac{1}{j\omega L_{add}}\right)V \tag{2}$$

however, an additional capacitance and inductance due to the additional field inside the metal or equivalently to the kinetic energy of the electrons is given by {how are equations 1 and 2 the related?}

$$C_{add}^{'} = \frac{\varepsilon_0 wt}{l} \qquad L_{add} = \frac{l}{\varepsilon_0 wt\omega_p^2} \tag{3}$$

The resonant frequency of the Split Ring hence formed is given by

$$\omega_0 = \frac{1}{\sqrt{(L + L_{add})(C + C_{add})}} \tag{4}$$

This additional inductance is dependent on the plasma frequency of the metal, which is equal to 3750 THz for aluminium and 2175 THz for gold [11]. Therefore there is added inductance for aluminium (as it is inversely proportional to the plasma frequency - and therefore a shorter resonance wavelength.

		TE Polarisation Resonant Wavelengths (microns)					
Sample	Unit cell	LC Aluminium			LC Gold		
		Exp	FD TD	Equivalent circuit	Exp	FDTD	Equivalent circuit
SRR	⊓	1.82	2.2	1.77	2.33	2.3	2.39

Table. 1. Comparison of LC resonance position from experiment with that calculated using an FDTD simulation and the modified equivalent circuit model.

6. CONCLUSIONS

An additional inductance term due to the non-ideal behaviour of metals at optical frequencies introduces a metal dependant term, which correctly explains the impact of changing from gold to aluminium. The effect of the wires on the LC resonance is to broaden them to shorter wavelengths. The strong and clear LC peak in aluminium is available for use switchable structures that operate at standard telecommunications wavelengths.

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