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Light propagation in multilayer metamaterials

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Planar single periodic metal/dielectric multilayer UV flat lens

We demonstrate a flat lens formed by a multilayer stack of 53 nm silver and 25 nm titanium dioxide films. The multilayer stack is designed to exhibit negative refraction of energy in the UV ($\lambda_0 = 364$ nm) spectral range. The metal and dielectric multilayer stack is fabricated using physical vapour deposition. Confocal microscopy is used to directly observe the image of a narrow slit formed above the lens surface, 790 nm from the object. The lens focus has an in-plane full width half maximum of 350 nm, in good agreement with calculations. Near field scanning optical microscopy measurements are performed to observe the 2D image of a 10 $\mu$m long slit. The simple planar multilayer design has several unique features such as a submicron thickness, the absence of an optical axis, and a lens-image separation in the 100 nanometer range.

4.1 Introduction

The refraction of light at an interface between two dielectrics is determined by the refractive index of the two media. A simple and elegant law, drafted by the Dutch scientist Snellius in the 17th century, relates the incident and outgoing angles of light at an interface to the ratio of the two refractive indices:
Snell’s law is valid for any refractive index provided by natural materials, typically in the range \( n = 1.0 - 4.5 \). Most recently, this range of indices has been expanded, with the advent of optical metamaterials: engineered composite materials of which the effective optical properties are determined by the bulk properties of the constituent materials in combination with a suitably designed sub-wavelength material architecture [68]. For example, a metamaterial composed of a sub-wavelength stack of dielectric rods can have an effective refractive index near zero [69]. An array of metal/dielectric thin films can be characterized by an effective permittivity close to zero, as was shown in Chapter 2. Also, materials with an effective index that is negative have been experimentally realized [8–10]. Even for these new materials with an unusual refractive index Snell’s law still describes how light is refracted at an interface.

In the 1960s, Veselago realized that, given Snell’s law, a thin slab of negative-index material would act as a flat lens [5]. Light incident from free space on a negative-index material slab will show negative refraction (i.e. refraction towards the same side of the surface normal as the incident beam, see Fig. 4.1a), at both the incoming and the outgoing interface. As a result, an initially diverging beam of light originating from an object refracts at the flat lens surfaces and will leave the negative-index slab as a converging beam, creating a focus on the other side. Such a lens design has many appealing aspects. First of all, it enables the lens to be very thin, as opposed to a conventional lens that operates based on the refraction of light at a convexly or concavely shaped lens surface, and which typically has a thickness in the millimeter range. In contrast, a flat negative-index lens will create a focus even if it is only a wavelength thick. Second, the object does not have to be placed at the focal length to obtain an image, but rather can be placed over a range of distances from the lens. Third, for a negative-index flat lens the image is a linearly translated copy of the object, while for a conventional lens the image has an inverted orientation. And fourth, a flat lens has no fixed optical axis, so an entire 2D plane can be imaged.

Optical metamaterials showing negative refraction have been demonstrated by several groups, first in the microwave range [7, 8], and later in the infrared [9, 10] and near-infrared spectral range [11]. Such materials are sometimes also referred to as “left-handed” metamaterials, as the \( E, H \) and \( k \) vectors form a left-handed system. These materials were made using resonant plasmonic nanostructures such as split ring resonators and fishnet structures. An alternative metamaterial design, based on coupled plasmonic waveguides arranged in a metal/dielectric multilayer stack was designed by Verhagen et al. [21] This geometry operates at much shorter wavelength, in the blue and ultraviolet spectral range, and exhibits negative refraction and flat lensing [57] for TM polarized light.

Hyperbolic metamaterials (HMMs) also show negative refraction [67, 70–73]. The effective permittivity of these metamaterials is anisotropic, with a tangential and longitudinal permittivity of opposite sign. This anisotropy leads to a hyperbolic dispersion relation describing light propagation through the metamaterial. The occurrence of negative refraction is easily visualised in a wavevector diagram (see
4.1 Introduction

(a) (b)

Figure 4.1: a, Sketch of a flat lens formed by a hypothetical \( n = -1 \) material. b, Schematic of the multilayer metamaterial structure considered here; gray layers correspond to Ag, with thickness \( d_m \) and blue layers to TiO\(_2\) with thickness \( d_d \). The unit cell size is defined as \( a \).

Fig. 1.2c). The permittivity tensor is:

\[
\varepsilon = \begin{pmatrix}
\epsilon_t & 0 & 0 \\
0 & \epsilon_t & 0 \\
0 & 0 & \epsilon_z
\end{pmatrix}
\]  

(4.1)

where \( \epsilon_t \epsilon_z < 0 \). The dispersion relation is given by \( k_z^2 = k_x^2/\epsilon_t + k_x^2/\epsilon_z \). For a metal dielectric stack with a deeply sub-wavelength unit cell size, \( \epsilon_t \) and \( \epsilon_z \) are given by effective medium theory as:

\[
\epsilon_t = (\epsilon_d d_d + \epsilon_m d_m)/(d_d + d_m) \quad \text{and} \quad \epsilon_z = ((\epsilon_d^{-1} d_d + \epsilon_m^{-1} d_m)/(d_d + d_m))^{-1}
\]

Figure 4.1b shows a sketch of the geometry considered in the following; an Ag layer of thickness \( d_m \) and a TiO\(_2\) layer of thickness \( d_d \) form the unit cell of the periodic multilayer.

Figure 4.2a shows the calculated wavevector diagram \( k_z(k_x) \) obtained from the effective medium theory (red) for an infinite Ag/TiO\(_2\) multilayer stack with very thin layers (the unit cell size is \( a = d_m + d_d = 1 \) nm, with \( d_m = 3d_d \)) for a freespace wavelength of 364 nm. We take measured values for the permittivity of Ag (\( \epsilon_m = -1.762 + 0.269i \)), and TiO\(_2\) (\( \epsilon_d = 7.270 + 0.163i \)) at \( \lambda_0 = 364 \) nm. First, we assume the lossless case, so we neglect the imaginary parts. The Bloch wavevector corresponding to this multilayer structure is determined as a function of parallel wavevector \( k_x \) using transfer matrix calculations (green). This result agrees very well with effective medium theory. The arrows drawn in Fig. 4.2a indicate the constructed refraction using this wave vector diagram for light incident from air at 30° on a semi-infinite region of this HMM geometry. As parallel wavevector momentum is conserved, the intersection of the dashed line in Fig. 4.2a with the isofrequency contour gives the refracted wavevector \( k_{\text{refr}} \) (red). The Poynting vector \( S_{\text{refr}} \) (purple) direction is given by the derivative \( \partial \omega / \partial k \), which is normal to the tangent at this point. This direction is determined by calculating the wavevector diagram at different \( \lambda_0 \) (not shown). As can be seen, the Poynting vector is oriented in the negative \( x \) direction, indicating negative refraction of energy.
Figure 4.2: a, Hyperbolic IFC calculated for $\lambda_0 = 364$ nm ($k_0 = 17.3$ $\mu$m$^{-1}$) described by effective medium theory (red), a periodic Ag/TiO$_2$ multilayer structure with a 1 nm unit cell (green), with $d_m = 3d_d$ and excluding losses. Increasing the unit cell to 50 nm bends the IFC away from a hyperbole (blue). The vertical dashed line corresponds to the parallel momentum of a plane wave in air incident at $30^\circ$. The Poynting vector shows negative refraction. b, Calculated Poynting vector angle for the hyperbolic metamaterial (red), ideal spherical IFC (green) and realistic geometry including losses (blue). The black dashed line corresponds to the ideal case $\theta_{ref} = -\theta_{inc}$. c, Increasing the unit cell size from $a = 1$ nm to $a = 100$ nm changes the curvature of the IFC. For a unit cell size of $a = 86.0$ nm, with $d_m = 64.6$ nm and $d_d = 21.4$ nm the curvature is spherical, with a radius equal to $k_0$ (black dashed curve). d, Including losses, the IFC changes shape (blue, green is lossless from c), but up to large angles ($55^\circ$) the curvature is the same.
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The Poynting vector angle (−7°) strongly deviates from the incident angle (30°). Fig. 4.2b shows the calculated refraction angle as a function of angle of incidence for the HMM (red line). The ideal case, required for flat lensing, given by $\theta_{\text{refr}} = -\theta_{\text{inc}}$ is indicated by the black dashed line. As is clear from the figure, a HMM does not satisfy this requirement. This makes a hyperbolic metamaterial design unsuitable to realize a flat lens, as it would exhibit strong aberrations, leading to a poorly defined focus [50, 75, 76].

To solve this problem, we investigate the effect of increasing the unit cell size. Figure 4.2a (blue) shows the IFC for a HMM in which the unit cell size is increased by a factor 50. Now, the IFC no longer agrees with the effective medium result. The deviation is more pronounced for large wavevectors, as then the internal field is more sensitive to the microscopic structure of the metamaterial. Fig. 4.2c shows how the IFC changes when gradually increasing the unit cell size from 1 to 100 nm, maintaining the ratio of metal and dielectric thickness fixed. The curve transforms from hyperbolic to spherical, centered around the band edge, $k_z = \pi / a$. Interestingly, if the layer thicknesses and material permittivity are chosen correctly, the curvature of the IFC can be matched very well to that of free space, given by a circle of radius $k_0 = 2\pi / \lambda_0$ (dashed line). At a wavelength of $\lambda_0 = 364$ nm, the optimum is found for $a = 86.0$ nm, with $d_m = 64.6$ nm and $d_d = 21.4$ nm. The realized spherical IFC implies that for all incident angles energy will be refracted with a negative angle equal in magnitude to the positive angle of incidence. The green line in Fig 4.2b shows the calculated Poynting vector angle for the optimum geometry. The angular response is indeed very close to the ideal curve for a large range of angles.

The IFC of this metamaterial design is fundamentally different from the IFC of the coupled waveguide design [21, 57]. There, the IFC of the fundamental harmonic is also spherical in shape, but oriented around the origin of the wavevector diagram. For the new design proposed here, the IFC is centered around the band edge. This means that in our design no guided modes exist along the metal/dielectric interfaces. However, for the purpose of creating a flat lens, the response is the same, with the exception that our new design has a phase difference between object and image, as will be discussed further on.

It should be noted that a similar multilayer geometry was considered earlier [77]. In that work, the IFC was also designed to be spherical, but with a radius of curvature larger than that of freespace. This has the advantage of also allowing the propagation of evanescent waves, which are attenuated in our design. However, a flat lens with such an IFC has aberrations, and can only produce a partial focus.

The above calculations were performed for lossless materials. Next, we consider realistic material losses, taking into account the complex permittivity of Ag and TiO$_2$. Fig. 4.2d shows the IFCs of this lossy multilayer geometry with layer thicknesses $d_m = 64.6$ nm and $d_d = 21.4$ nm (blue). The lossless case is also plotted again for reference (green). As can be seen, the IFC is nearly spherical for $k_x < 14 \, \mu m^{-1}$, corresponding to an angle of incidence of about 55°. At larger angles, the IFC significantly deviates from the spherical shape. In this wavevector regime, most of the field is localized in the metal layers, which are strongly absorbing. The
calculated Poynting vector angle for this geometry is shown in Fig. 4.2b (blue). As expected, it is very close to the ideal curve (black dashed) for angles of incidence below 55°.

To evaluate the imaging performance of this metamaterial design, we investigate the precise shape of the IFC, and define the deviation from an ideal spherical IFC as:

\[
D = \frac{1}{k_0} \int_0^{k_0} |\pi/a - \sqrt{k_0^2 - k_x^2 - k_{B1}(k_x)}| \, dk_x
\]

(4.2)

Figure 4.3 shows the value of \(D\) as a function of metal and dielectric layer thickness. As can be seen, there is a wide band of combinations of \(d_m\) and \(d_d\) for which \(D\) is very low. All points on this band lead to an IFC with a curvature very close to that of free space, corresponding to an angle-independent response. This emulates the negative refraction observed in a \(n = -1\) material for propagating waves, and enables the realization of a flat lens.

![Figure 4.3: Plot of deviation D from the ideal IFC curve as a function of metal (d_m) and dielectric (d_d) layer thickness. Optimization of the layer thicknesses reveals a broad band of combinations of metal and dielectric layer thicknesses achieving an isofrequency contour which is very close to ideal (blue). These structures have an IFC with a spherical shape and radius k_0.](image)

4.2 **Poynting vector angle**

Analysis of the Poynting vector angle as above strictly holds only for lossless and infinitely periodic structures [30]. To investigate how light refracts and propagates in a lossy, finite sized, multilayer system, we calculate the Poynting vector angle...
from the lateral shift of a quasi plane wave propagating through the flat lens. It has been shown that the lateral shift is proportional to the derivative of the phase of the transmitted electric field with respect to the parallel wavevector component \[ \Delta = \partial (-\arg(t(k_x)))/\partial k_x, \]
where the phase is given by the argument of the transmission coefficient \( t \). The Poynting vector refraction angle is then defined as \( \tan(\theta_t) = \Delta/L \), where \( L \) is the total slab thickness.

![Figure 4.4: Construction of the Poynting vector angle from \( S \parallel \partial \omega/\partial k \) for the ideal geometry with losses (black). The colored lines correspond to the Poynting vector angle defined as \( \tan(\theta_t) = \Delta/L \), where \( \Delta \) is the lateral shift and \( L \) is the total slab thickness, calculated for a changing number of unit cells (UC).](image)

Figure 4.4 shows the result of this calculation. The Poynting vector angle is calculated for a different number of unit cells in the range 1-10. The Poynting vector angle constructed from the IFC is shown for reference (black). As can be seen, when only one or two unit cells are considered the refraction angle deviates significantly from the curve obtained from the IFC. For a larger number of unit cells (\( \geq 5 \)), both analyses yield quite similar results for angles up to 60°. This further confirms that the metamaterial structure exhibits negative refraction when losses and a finite structure are taken into account. The deviations in Fig. 4.4 for the case of a small number of unit cells are due to multiple reflections inside such a finite slab; for a larger metamaterial thickness the back reflected waves are attenuated by absorption. Note that calculating the Poynting vector angle directly from the microscopic fields will neglect the macroscopic magnetization and therefore give a different result [79,81].
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4.3 Phase condition

In the previous section, we have shown how energy refracts negatively, allowing flat lensing. Apart from the direction of energy propagation, indicated by the Poynting vector, the direction of phase propagation, indicated by the wave vector, is also critical to realize a flat lens as the interference at the focal point should be constructive for all angles of incidence. If we first consider a hypothetical slab of left-handed \((k \cdot S < 0)\) \(n = -1\) material, as Veselago did originally, it is easy to see how this condition is fulfilled. Figure 4.5 shows a sketch of the geometry. Light is emitted from a source at \((x_s, z_s)\), and propagates with angle \(\theta_i\) towards the \(n = -1\) slab. Parallel wave vector conservation over the \(n = 1/n = -1\) interface completely determines refraction. From the construction it is clear that \(L = d_s + d_i\), with \(L\) the lens thickness, \(d_s\) the lens-source separation, and \(d_i\) the lens-image separation. The wave vector \(k_{mm}\) inside the slab is oriented exactly anti-parallel to the direction of propagation of energy. If we decompose the phase advance, the lateral \(x\)-component drops out, as there is no net propagation in that direction. The total phase advance in the longitudinal \(z\)-direction is also zero, as the vertical component \(k_z\) changes sign inside the slab; \(k_z = -\sqrt{k_0^2 - k_x^2}\). Therefore the positive phase advance \(\phi_a = k_z(d_s + d_i)\) in the air region is compensated by the negative phase accruing in the \(n = -1\) slab; \(\phi_s = -k_zL\). Following the construction in Fig. 4.5 it is clear the phase at the image position \((x_s, z_i)\) is equal to the phase at the source position \((x_s, z_s)\): \(\phi_t = \phi_a + \phi_s = 0\).

\[\phi_t = \phi_a + \phi_s = 0\]

\[\phi_t = \phi_a + \phi_s = 0\]

\[\phi_t = \phi_a + \phi_s = 0\]

**Figure 4.5:** Sketch of the propagation of light from a source (red) through a hypothetical \(n = -1\) metamaterial slab. Negative refraction occurs over the \(air/n = -1\) interfaces, and in the \(n = -1\) slab the phase (indicated by \(k_{mm}\)) is propagating anti-parallel to energy (black arrows). The total slab thickness \(L\) is equal to the sum of the lens-source separation \(d_s\) and the lens-image separation \(d_i\).

From Fig. 4.5 we can evaluate the relative orientation of \(k\) and \(S\) in the mul-
tilayer structure. As is clear, $k \cdot S > 0$ for all angles, so this metamaterial is right-handed. However, when the IFC of the multilayer geometry is spherical, the structure can fulfill the condition of constructive interference at the image position. In the wavevector diagram $k_z$ is given by $k_z = k_{Bl} + \frac{2\pi}{a} m$. Here, $k_{Bl}$ is the Bloch wave vector, $m$ is an integer corresponding to the Bloch wave harmonic [82], and $a$ is the unit cell size. In the ideal case we can simplify $k_{Bl} = \pi / a - \sqrt{k_0^2 - k_x^2}$. The total phase advance from source to image will then be: $\phi_t = k_z (d_s + d_i) + (\pi / a - \sqrt{k_0^2 - k_x^2} + \frac{2\pi}{a} m) L$. If the multilayer structure is constructed from an integer number of unit cells; $L = j a$, then $\phi_t = \pi j (1 + 2m)$. The phases in source and image thus differ by $\pi j$. Importantly, the phase difference is independent of angle, and therefore interference at the image position is constructive.

The analysis above indicated that although light propagation through the metal/dielectric multilayer is very different from propagation through a hypothetical homogeneous $n = -1$ slab, it will act as a flat lens. In the next section, we show how we fabricate and characterize this multilayer lens.

### 4.4 Sample fabrication

The optimized metamaterial geometry was designed for a wavelength of operation of $\lambda_0 = 364$ nm, with $d_m = 53.2$ nm and $d_d = 25.0$ nm. These layer thicknesses are slightly different than those in section 4.2 as they are optimized for the dielectric constants observed for the deposited layers. We deposit multilayer stacks consisting of an integer number of unit cells using physical vapor deposition (PVD). Here, a 10 kV electron beam is used to heat Ag and Ti$_3$O$_5$ pellets placed in separate crucibles. During deposition, the layer thickness is monitored using a quartz crystal thickness monitor, which we calibrated by depositing single films on separate Si substrates. The optical constants and thickness of these individual reference layers were then measured using spectroscopic ellipsometry. After this calibration a complete multilayer stack is deposited. Figure 4.6a shows a scanning electron microscope (SEM) image of a cross section of a 4-unit-cell stack deposited on a SiN film on Si, made using focused ion beam (FIB) milling. The bright bands correspond to the Ag layers, and the darker bands to TiO$_2$. The multilayer was covered with Pt before milling to obtain a clear cross section.

Figure 4.6b shows an optical microscope image of a multilayer stack deposited on top of a 50 nm thick silicon nitride membrane (Norcada NX5025A), which has a clear window of 250 $\mu$m $\times$ 250 $\mu$m, allowing optical transmission measurements. Before deposition of the multilayer stack, the SiN membrane was first covered with 800 nm of MMA and 80 nm of PMMA. Patches of 25 $\mu$m by 25 $\mu$m were then exposed using electron beam lithography and developed using MIBK:IPA. This allows us to lift off part of the deposited multilayer structure, in order to obtain a reference in the flat lens experiment. The rear side of the silicon nitride membrane was sputter-coated with 150 nm of Cr, acting as an optically thick masking layer. FIB
Figure 4.6: **a**, SEM image of a cross section of a fabricated multilayer structure. Four unit cells of Ag (light) and TiO$_2$ (dark) are clearly visible. The top TiO$_2$ layer is capped by Pt to make the FIB cross-section. This sample was studied using NSOM. **b**, Optical microscope image of multilayer structures (25 × 25 µm) deposited on a SiN membrane window. The other regions of the multilayer stack are removed by lift off. The opposite side of the membrane window is coated with a Cr masking layer, in which slits are written using FIB, acting as an object. This sample was studied using confocal microscopy. **c**, SEM image of a 200 nm wide slit in the Cr masking layer. The underlying SiN is exposed.
milling was then used to create 100 nm wide and 10 µm long slits through the opaque Cr layer. Figure 4.6c shows a SEM image of a slit through the Cr masking layer. These slits serve as the objects for the flat lens: the light scattered by the slit propagates through the thin SiN membrane, and is then negatively refracted by the flat lens. A focus is formed in the air region above the flat lens, establishing an image. As a reference, we have also written slits in the Cr layer at positions of the membrane where the deposited multilayer stack was lifted off. Here, the scattered light propagates through the 50 nm SiN, and then further diverges in free space.

![Graph](image)

**Figure 4.7:** Measured reflection (red) and transmission (blue) of fabricated 4-unit-cell Ag/TiO₂ multilayer deposited on a glass microscope slide. The thin solid line corresponds to the calculated result, based on deposited layer thicknesses and optical constants. A slightly lower reflection and higher transmission is observed in the experimental data, which is attributed to surface roughness in the metal layers.

To study the optical properties of the fabricated multilayer, we perform specular reflection and transmission measurements at an angle of incidence of 20° on a multilayer sample consisting of four unit cells deposited on a glass microscope slide. Figure 4.7 shows the measured data (dots). Overall, the trends in the observed reflection and transmission spectra agree very well with the data from a transfer matrix calculation (thin lines). These calculations used layer thicknesses and optical constants experimentally determined from spectroscopic ellipsometry measurements on individual reference layers. The differences in absolute values are attributed to surface roughness, especially in the thin metal films, which is inherent in the PVD process. Scattering from this roughness is not taken into account in our calculations.
4.5 Experiments

To characterize the focusing properties of the metal dielectric multilayer stack, we measure the image of the slit milled in the Cr film on the other side of the SiN membrane. The total lens thickness is 390 nm, and the distance from the object to the lens is 50 nm (the SiN membrane thickness). Therefore we expect a lens-image separation of 340 nm. We use a Witec alphaSNOM confocal microscope to weakly focus $\lambda_0 = 364$ nm light from an Ar ion laser on the object slit (see Fig. 4.8a). The transmitted light is imaged on a fiber core (25 $\mu$m diameter), and sent to a spectrometer. The sample is scanned using a piezo-electric stage in the x-direction, normal to the slit. The incident beam and collection objective are kept fixed, such that the lateral transmission dependence is probed. Furthermore, the upper microscope body is scanned in height, to determine the vertical dependence of the image plane. The transmitted light is collected using a 100x objective (Zeiss Epiplan-NEOFLUAR 100X/0.9) providing a lateral resolution of approximately 200 nm at $\lambda_0 = 364$ nm. The result of this confocal measurement can be seen in Figure 4.8b. A clear focus is observed, confirming that the single-periodic multilayer structure acts as a flat lens. The minimum width of the focus coincides with a maximum in transmitted amplitude. We analyze the focal shape by taking a line cut for fixed microscope z-axis height. A Gaussian profile is fitted to the recorded signal, which is a good approximation to the focus shape near the focal position. The minimum full width half maximum (FWHM) we find is approximately 350 nm. As a comparison, we use analytical Green’s tensor calculations in a multilayer structure to calculate the spatial field formed by a horizontal dipole placed below the multilayer structure, and find a very similar FWHM. Furthermore, using Lumerical FDTD we have simulated the effect of changing the slit width, and see no significant change in the FWHM for a slit width below 200 nm.

To determine the vertical position of the focus above the lens surface, we image two object slits in a single scan. The first object slit is positioned underneath the flat lens. The second object slit is positioned at a region of the SiN membrane where the multilayer structure has been lifted off, as indicated by the sketch in Fig. 4.8a. By measuring the transmitted light from both slits in a single scan, we can accurately determine the focal position relative to the lens surface. Figure 4.9a shows the result of such a scan, with the amplitude plotted on a logarithmic scale. Light from the reference slit is much more intense as it is directly transmitted (left), whereas the light from the slit underneath the lens is partially reflected and partially absorbed, reducing the transmitted light intensity (right). The spatial intensity distribution is analyzed by taking line cuts through the data at a fixed height $z$. Figure 4.9b,c show the normalized fitted amplitude and Gaussian width of both the reference (red) and the sample (blue) signal. As can be seen, the maximum amplitude and minimum width correspond to the same position for both reference and sample. Taking the peak in amplitude and minimum in width of the reference signal as the height where the object slit is in focus, we find that the focus formed by the flat lens is positioned 790 nm away from the object, which is 350 nm above the top.
4.5 Experiments

Figure 4.8: a, Sketch of the confocal microscope setup. The incident beam is weakly focussed on the object slit. The sample stage is scanned in the lateral $x$ direction. The top collection arm of the microscope body is scanned in the vertical $z$ direction. 

b, Normalized transmission as a function of lateral sample position $x$ and vertical microscope body position $z$. A clear image of the slit is observed.

Figure 4.9: a, Confocal scan ($\lambda_0 = 364$ nm) of the signal of a reference slit (left) and sample slit (right) above the multilayer metamaterial. The normalized transmitted signal is plotted on a $\log_{10}$ scale. There is a large amplitude difference between reference and sample due to the reflection and absorption of the multilayer stack.

Normalized amplitude (b) and width (c) of the fitted Gaussian profile as a function of $z$. A clear vertical offset of 790 nm is observed between the reference (red) and sample (blue) signal; the corresponding distance between lens surface and focus is 350 nm.
Planar single periodic metal/dielectric multilayer UV flat lens interface. This agrees very well with the lens-image separation of 340 nm, calculated using \( L = d_s + d_i \).

![Figure 4.10: a, Sketch of the near field scanning optical microscope experiment. The sample is scanned beneath the hollow Al tip. b, Spatial image of the transmitted light intensity, at \( \lambda_0 = 364 \) nm, and with the NSOM tip in contact with the flat lens. Almost no signal is observed. c, The same spatial scan, with the NSOM tip suspended 220 nm above the flat lens. An image of the object slit is observed. Note the difference in intensity scales between (b) and (c).](image)

To study the spatial structure of the transmitted signal in further detail, we perform near-field scanning optical microscopy (NSOM) using a hollow Al tip with a 150 nm diameter aperture (Witec). Figure 4.10a shows a sketch of this experimental geometry. The multilayer structure for these experiments was composed of four unit cells, with \( d_m = 57.3 \) nm and \( d_d = 25.8 \) nm. Calculations show that a focus is expected 190 nm above the lens surface. First, we position the near-field tip in contact with the multilayer surface, and scan the sample in the \((x, y)\) dimensions. Figure 4.10b is a spatial map of the transmitted intensity. A contour of the slit geometry is observed, but at very low intensity. Next, the tip is retracted from the surface, and is suspended approximately 220 nm above the surface (as determined from the force-distance curve of the tip) and the same lateral scan is performed (Fig. 4.10c). When compared with the scan in contact mode, the signal-to-noise level is much higher. This is consistent with the expectation that the tip is closer to the image plane above the flat lens.

As is clear from Fig. 4.10c, the transmitted intensity shows strong variations across the slit length. We attribute these variations to scattering from Ag grains within the multilayer stack. Such grains are evident in the SEM image of the cross-section (Fig. 4.6a). To optimize the flat lens, the Ag deposition conditions could be
fine tuned to reduce the effect of this grain structures. Recent work, using template stripping [83], using an adhesion layer [84, 85] or sputter coating at high deposition rates on a heated substrate [86], show that smoother Ag films can be experimentally realized.

4.6 Conclusions

In conclusion, we designed a planar multilayer geometry that acts as a flat lens. We use a hyperbolic metamaterial formed by a Ag/TiO$_2$ multilayer stack with a very small unit cell size as a starting point, and gradually increase the unit cell size far above the effective medium approximation limit. Using properly chosen layer thicknesses the isofrequency contour can be designed to be spherical in shape, with a radius equal to that for the contour in free space. This geometry shows all-angle negative refraction, and can therefore act as a flat lens. An optimized flat lens geometry based on a Ag/TiO$_2$ multilayer stack, with layer thicknesses $d_m = 53.2$ nm and $d_d = 25.0$ nm, is fabricated using physical vapor deposition. We use confocal microscopy at $\lambda_0 = 364$ nm to study the spatial shape of the image of a linear object slit placed below the flat lens. A clear focus is resolved above the lens with a full width half maximum of 350 nm. We find that the image is positioned 350 nm from the lens surface, as expected. Near-field scanning optical microscopy confirms the image is formed above the lens. The single-periodic design is fundamentally different from the double periodic design demonstrated earlier that is based on coupled plasmonic waveguides, and it is easier to fabricate. The flat lens has properties unlike normal lenses; such as the absence of an optical axis, it has a submicron thickness, and the ability to form an image in the 100 nm range from the lens surface.