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Super-resolving Properties of Metallodielectric Stacks

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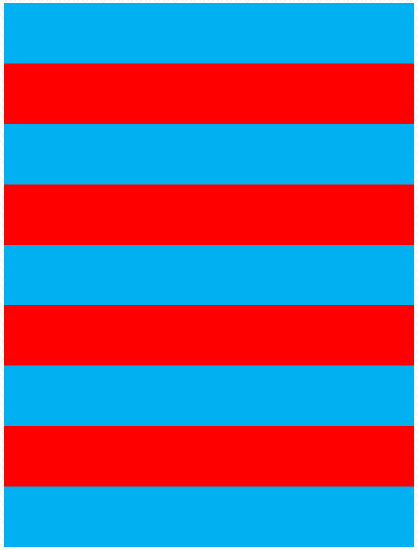
1 Introduction

Conventional optical imaging systems resolve only to about half the wavelength of incident light.

Goals

- UV-Vis wavelengths (400 – 700 nm)
- %T 100x greater than single layer Ag
- λ/12 spatial resolution

Operation of MDS



Suppress diffraction through balance of positive and negative refraction

2 Transmission and Super-resolution regimes

TMM formalism

$$E = (A_\alpha \exp(-i\,\beta_\alpha z) + B_\alpha \exp(i\,\beta_\alpha z))\exp(-i\kappa\, x)$$

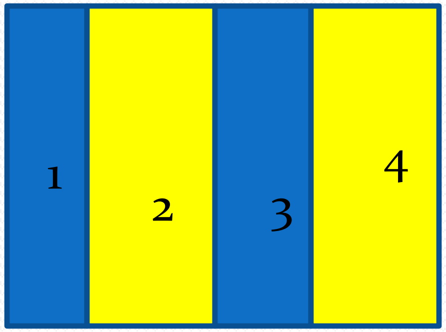
$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \frac{1}{t_{12}} \begin{bmatrix} 1 & r_{12} \\ r_{12} & 1 \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = T \begin{bmatrix} A_2 \\ B_2 \end{bmatrix}$$

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} \exp(i\ \phi) & 0 \\ 0 & \exp(-i\,\phi) \end{bmatrix} \begin{bmatrix} A' \\ B' \end{bmatrix} = P \begin{bmatrix} A' \\ B' \end{bmatrix}$$

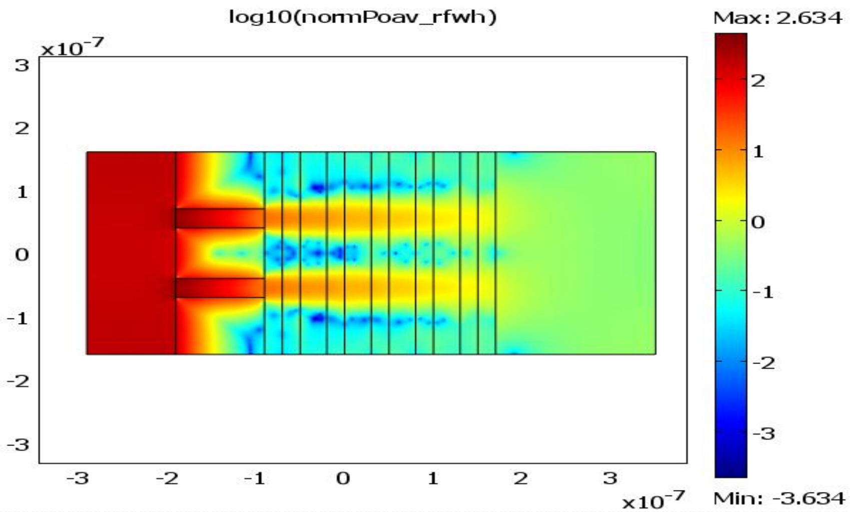
$$F = T_1 P_1 T_2 P_2 T_3 P_3 \ldots T_{n\ 1} P_n T_{n+1}$$

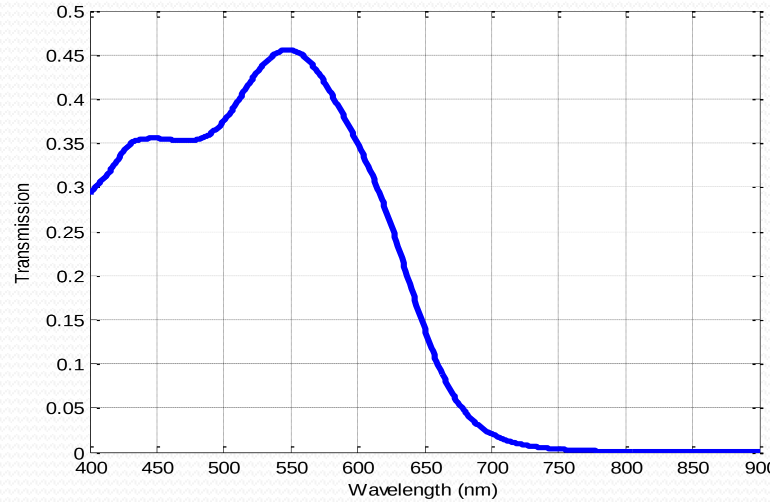
$$F = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix}$$

$$R = \left| \frac{f_{21}}{f_{11}} \right|^2, T = \left| \frac{1}{f_{11}} \right|^2$$

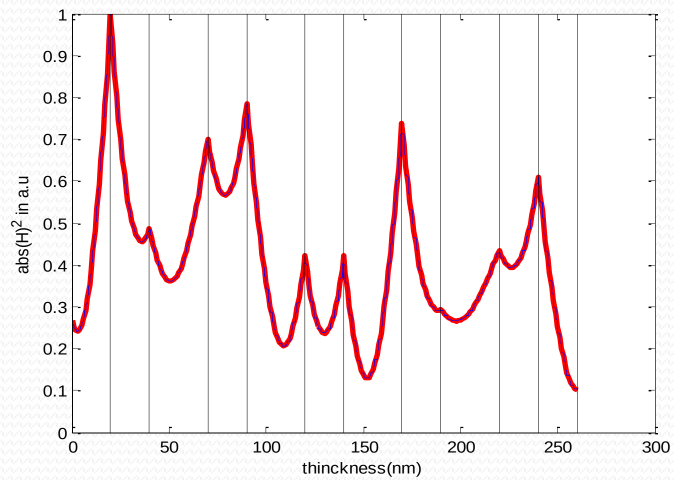


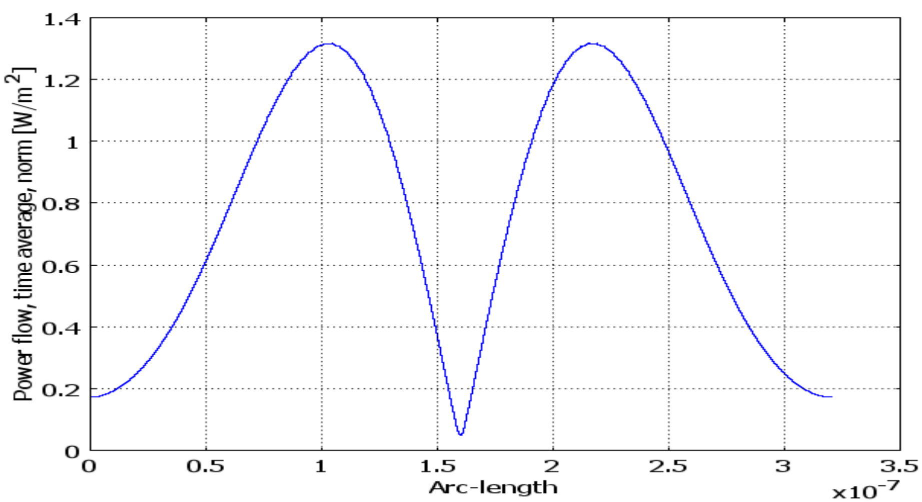
MDS1





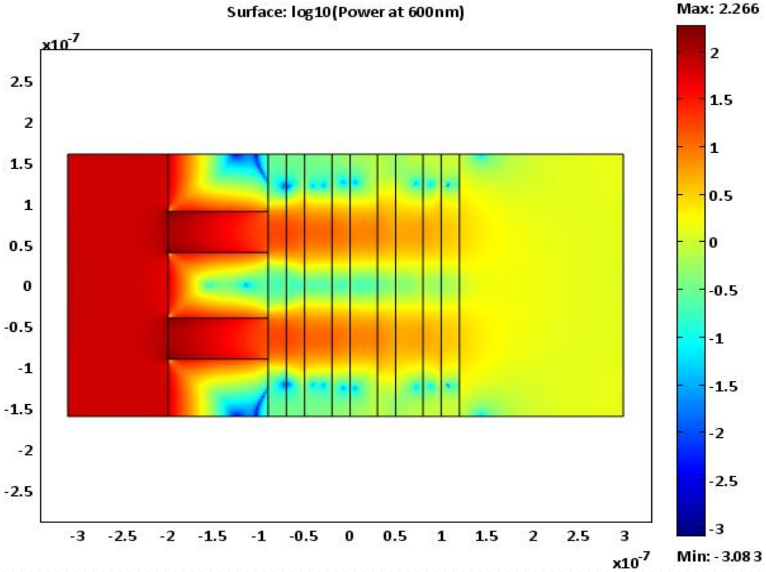
MDS1: [GaP (20nm)/ 4.5 periods of Ag (20nm)/ GaP (30nm) /GaP (20nm)].

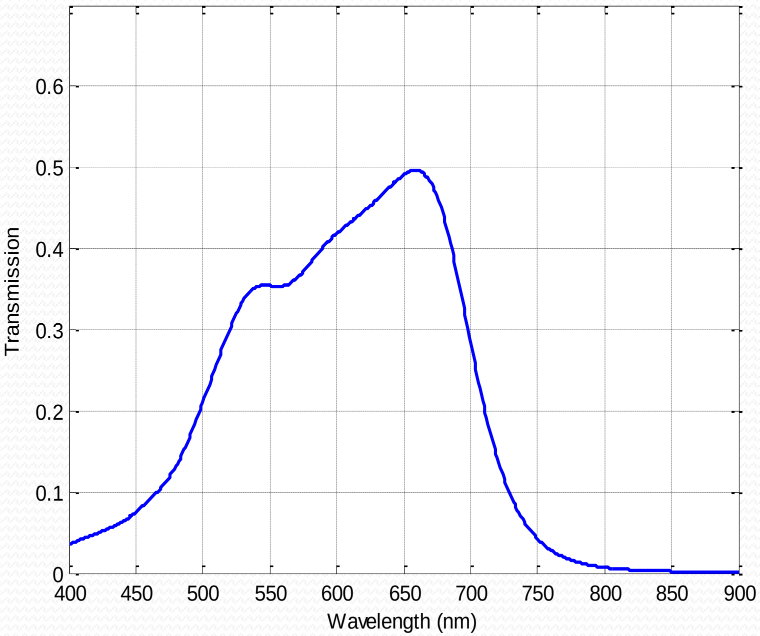




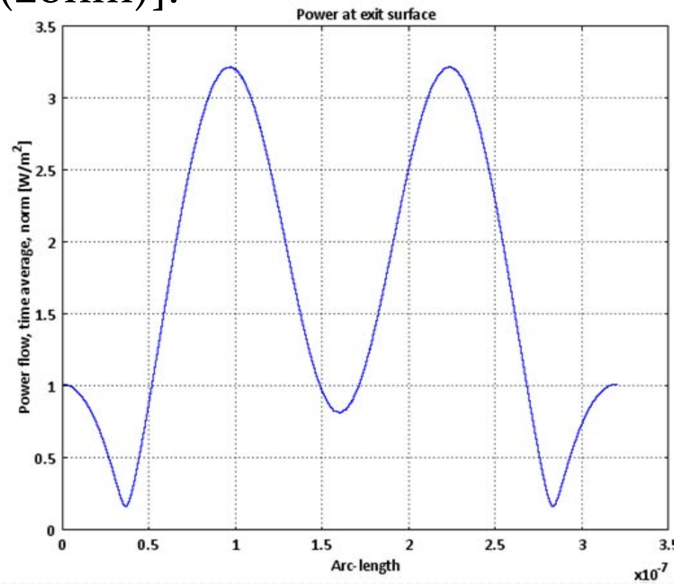
Plot of the Magnetic field squared across the thickness of MDS1 consisting of Ag and GaP layers. There is an overlay of the red line over the blue line. The red line is the FEM simulation . While the blue line is TMM solution . Both methods give a transmission of 44% at an incident wavelength of 532nm.

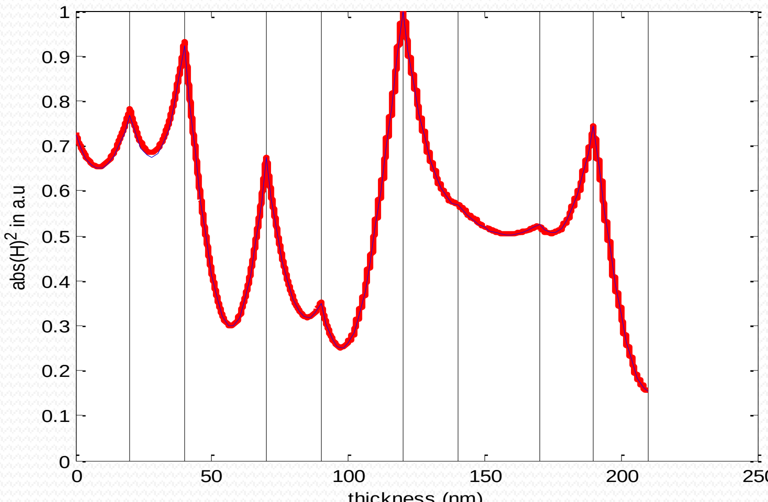
MDS2





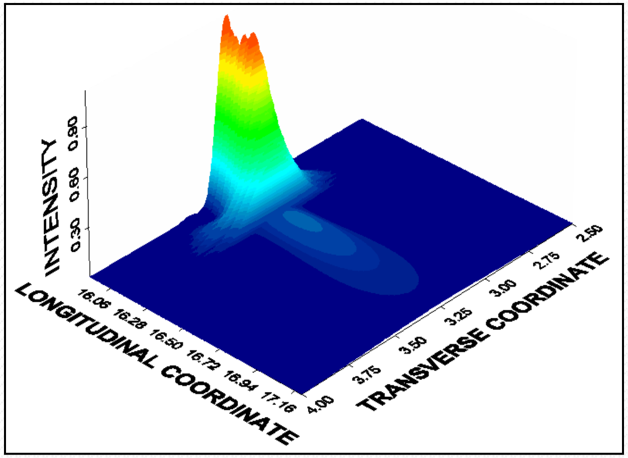
MDS2: [GaP (20nm)/3.5periods (Au (20nm)/GaP (30nm))/GaP (20nm)].

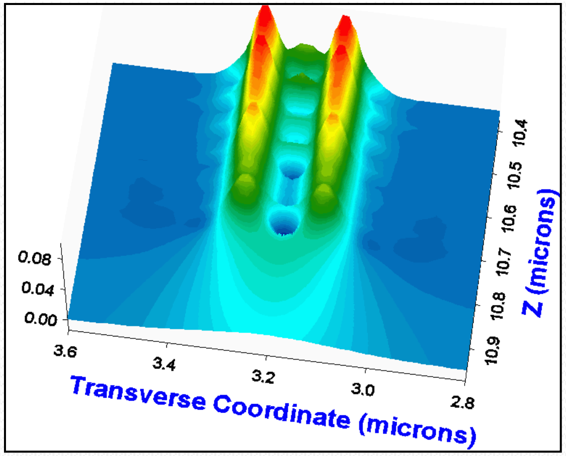




Plot of the Magnetic field square across the thickness of MDS2 consisting of Au and GaP layers. There is an overlay of the red line over the blue line. The red line is the FEM simulation . While the blue line is TMM solution . Both methods give a transmission of 42% at an incident wavelength of 600nm.

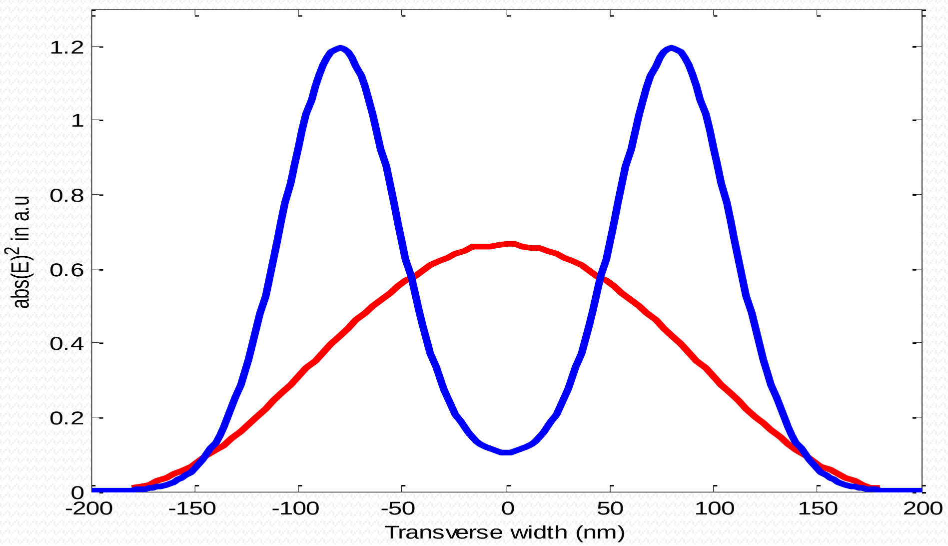
Beam Propagation results (Plane-wave method)





Transmission through a MD photonic crystal (the layers are parallel to the transverse coordinate) in the focusing regime (λ=400 nm), which shows the formation of an external focal spot (left), and in the super-resolving regime (right) showing the super-guiding regime (λ=640 nm), with two closely spaced λ/20 channels that do not interfere thanks to the formation of transverse Plasmon waves [4,7].

MDS3: Limitations of TMM



Comsol result: No Super-resolution Diffraction, unsuppressed.

Reason for discrepancy

•TMM field is prescribed on the surface and this is unphysical.
•Comsol the field propagates through a slit and the fields interact with the slit.

MDS3: [TiO2 (40nm)/ 3.5periods of (Cu (20nm)/TiO_2 (80nm)/TiO_2 (40nm)].

Nonlinear Photonics with MDS3

$$\mathbf{P}_{\mathbf{NL}} = \varepsilon_0 \chi^{(2)} \mathbf{E}\,\mathbf{E} \quad + \varepsilon_0 \chi^{(3)} \mathbf{E}\,\mathbf{E}\,\mathbf{E} \quad + \ldots$$

$$\nabla \times \nabla \times \mathbf{E} = -\mu_0 \left(\varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} + \frac{\partial^2 \mathbf{P}_{\mathbf{L}}}{\partial t^2} + \frac{\partial^2 \mathbf{P}_{\mathbf{NL}}}{\partial t^2} \right)$$

$$\nabla(\nabla \cdot E) - \nabla^2 E = -\mu_0 \left(\varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} + \frac{\partial^2 \mathbf{P}_{\mathbf{L}}}{\partial t^2} + \frac{\partial^2 \mathbf{P}_{\mathbf{NL}}}{\partial t^2} \right)$$

$$E(Z,r,t) = E_0(t) \frac{w_0}{w(Z)} \exp\left(-\frac{r^2}{w^2(Z)} + i \frac{\pi r^2}{\lambda R(Z)} + i\phi \right)$$

$$Z_0 = \frac{\pi w_0^2}{\lambda}$$

For CW $E_0(t) \rightarrow E_0$

Nonlinear absorption
And Nonlinear refraction
Applications (Optical limiting and Switching)

$$\chi^{(3)} \propto n_2 + i\beta$$

NL index change NL (two photon) absorption

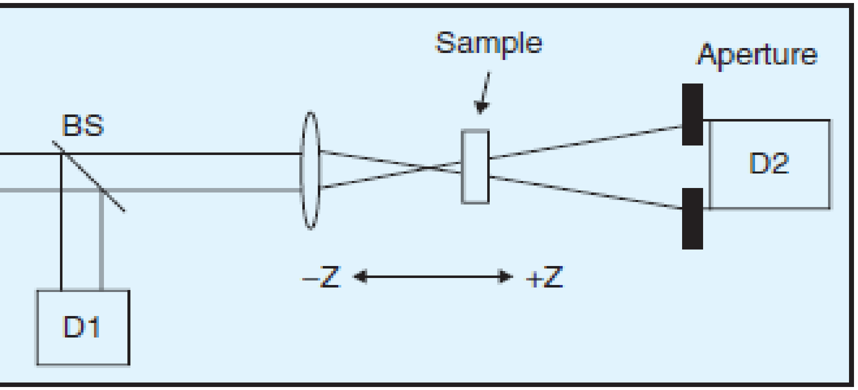
Implementation of a Paraxial Optical Propagation Method for Large Photonic Devices COMSOL Conf 2009
J. E Toney

"Cannot handle systems with arbitrary propagation directions: Photonic crystals (photonic band gaps)"

Z scan technique

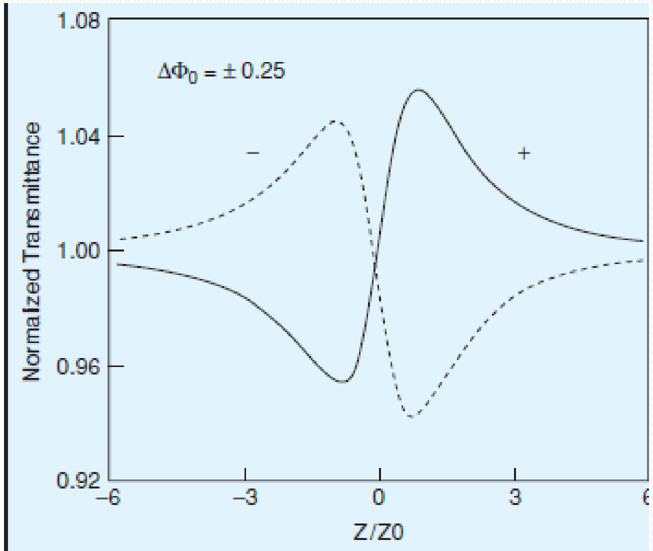
Developed for homogenous material, reliable for the determination of β and n2

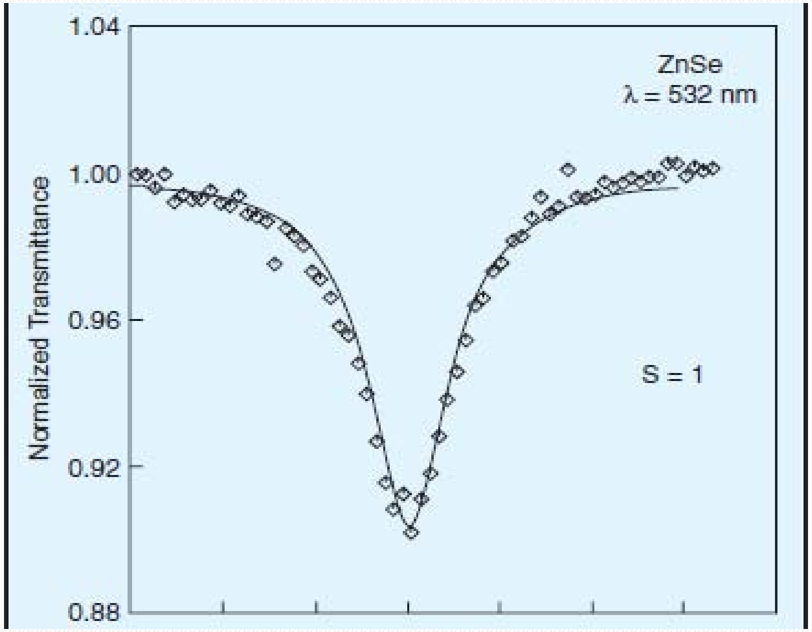
M. Sheik-Bahae, A. A. Said, T. Wei, D. J. Hagan, and E. W. Van Stryland, "Sensitive measurement of optical nonlinearities using a single beam," IEEE J. Quantum Electron. **26**, 760–769 (1990).



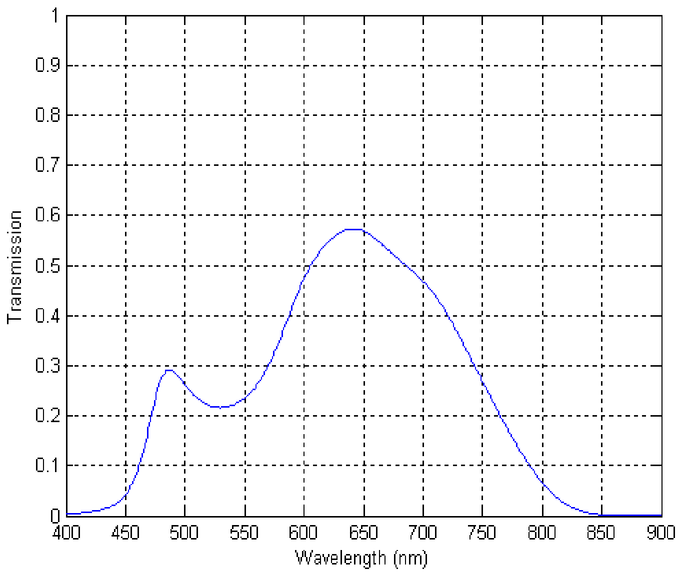
$$P_T(\Delta\Phi_0(t)) = c\epsilon_0 n_0 \pi \int_0^{r_a} | E_a(r,t) |^2 \, r dr$$

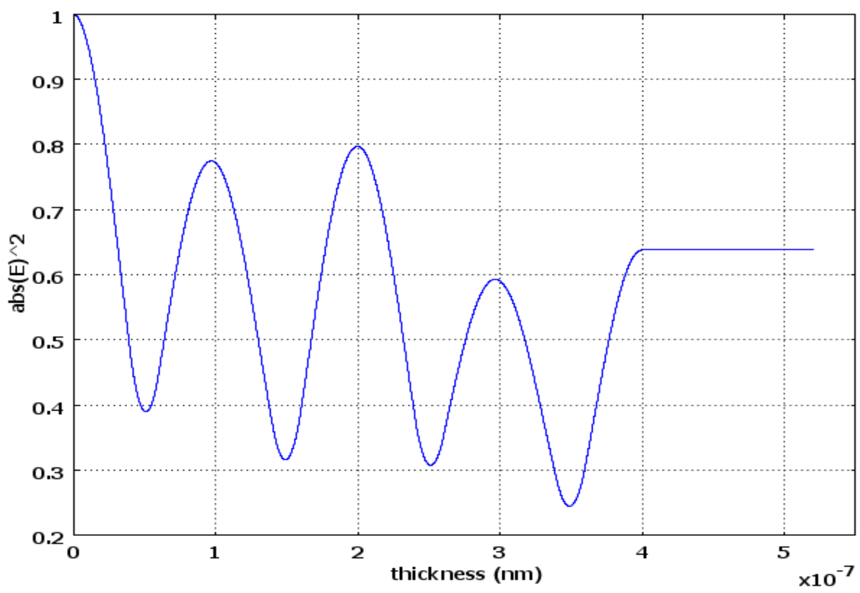
$$E_l(z,r,t) = E(z,r,t) e^{-\alpha L/2} e^{i\Delta\phi(z,r,t)}.$$

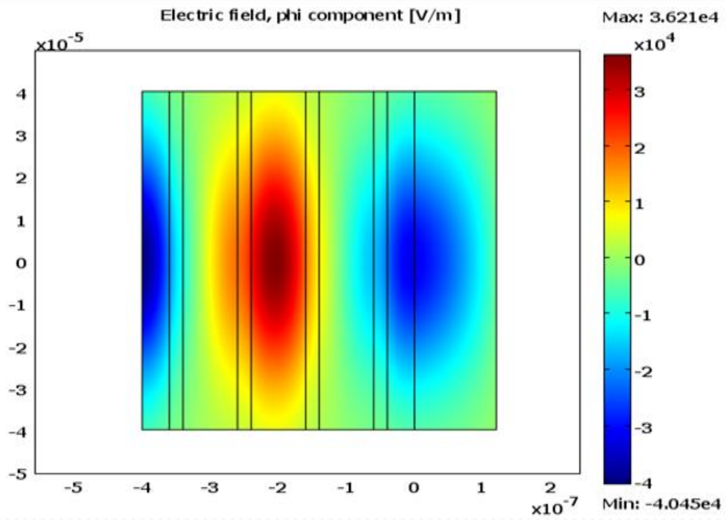


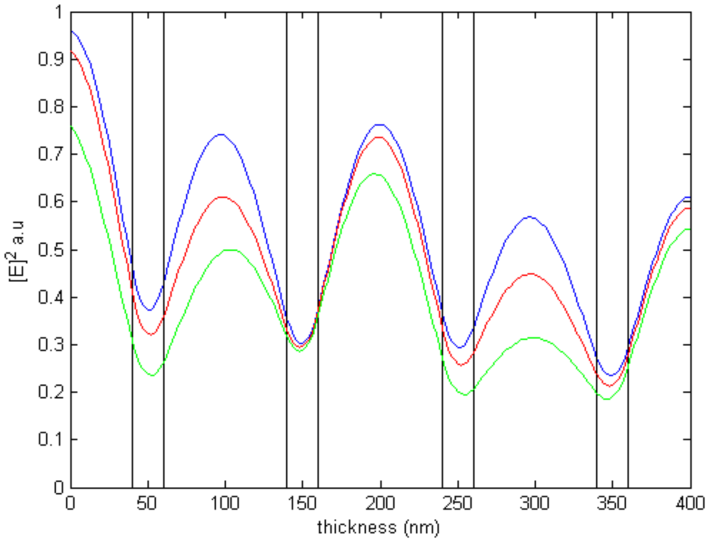


Results for MDS3



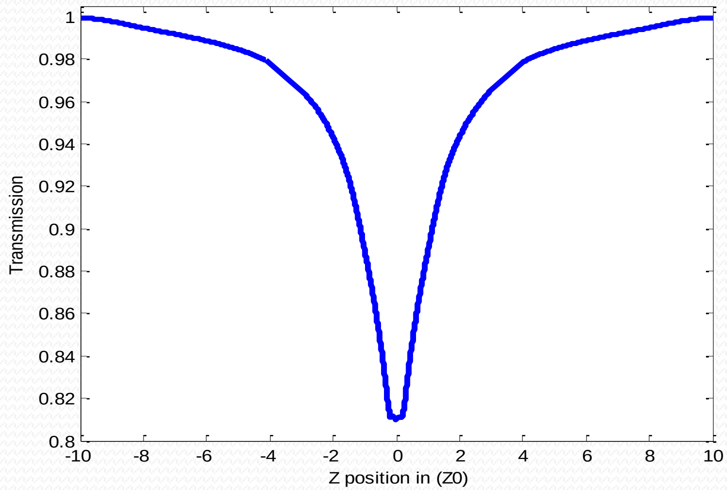






Open Aperture Z scan Result

-Simulation of a 1D photonic band gap device such as our MD stack usually Includes the losses due to internal multi-interference and back reflections, which contributes to the absorption within each layer .
-Considers transverse effects important in describing the beam profile are neglected [10]. These transverse effects are important for experimental purposes.
-Significant nonlinearity and realistic input beams,



$\beta = 4.75 \times 10^{-6} cm/W$

$n_2 = 2 \times 10^{-11} cm^2/W$

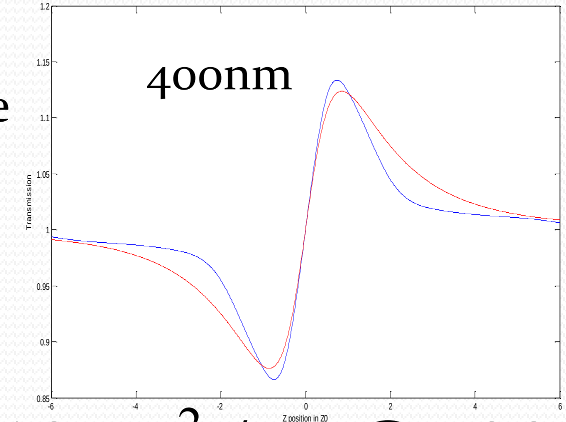
$$w_0 = 20\mu m$$

$$T(Z) = \frac{1}{U}\int_{-\infty}^{+\infty} dt \int_0^{r_a} rdr\,|E_a(Z,r,t,d|^2$$

$$T(Z) \cong 1 - \frac{4\Delta\phi_0 x}{(x^2+9)(x^2+1)}$$

Check for purely nonlinear refractive material,

FEM:blue
ANA:red



$$n_2 = 9e-12cm^2/W\,@532nm$$

Summary and conclusions

Super-resolution is achieved at various wavelengths with MDS.
Compared the TMM and the FEM for Transmission, and Super-resolution .We find that even though both methods yield the same results for Transmission, the standard TMM method fails to accurately predict Super-resolution.

Simulated the propagation of a typical Gaussian beam through a nonlinear MDS. The output of this simulation has been used to model the standard CW Z scan experiment, and the results agree very well with the Z scan theory

Future Work : Include temperature dependence for the permittivity and solve a transient problem.

Some References

[1] J. B. Pendry, “Negative refraction makes a perfect lens,” Phys. Rev. Lett. **85**, 3966 (2000).

[2] M. Scalora et al.“Negative refraction and sub-wavelength focusing in the visible range using transparent metallo-dielectric stacks,” Optics Express **15**, 508-523 (2007).

[3] M. J. Bloemer, G. D’Aguanno, N. Mattiucci, M. Scalora, and N. Akozbek, "Broadband super resolving lens with high transparency for propagating and evanescent waves in the visible range," http://www.arxiv.org/abs/physics/0611162.

[4] D. de Ceglia, M. A. Vincenti, M. G. Cappeddu, M. Centini, N. Akozbek, A. D’Orazio, J. W. Haus, M. J. Bloemer, and M. Scalora, Tailoring Metallodielectric Structures for Super Resolution and Super guiding Application in the Visible and near IR Ranges, Physical Rev. A **77**, 033848 (2008).

[5] E. D. Palik, Handbook of Optical Constants of Solids (Academic Press, New York, 1985).

[6]   C.P Moore, R. J. Blaikie, M. D. Arnold “ An improved transfer-matrix model for optical superlenses”, Optics Express **17**(16), 14260 (2009).

[7] J.W. Haus, N. Katte, J. B. Serushema and M. Scalora, “Metallodielectrics as Metamaterials,” “SPIE Optics and Photonics Conference, to appear (2010).

[8] M. Sheik-Bahae, A. A. Said, T. Wei, D. J. Hagan, and E. W. Van Stryland, “Sensitive measurement of optical nonlinearities using a single beam,” IEEE J. Quantum Electron. **26**, 760–769 (1990).

Simulation Details

*****Nonlinear Optics Simulation*****

Number of Mesh points =4305
Number of Mesh elements 4160
Number of degrees of Freedom=33858