Optical Negative Index Meta-materials at 1.55 μm Wavelength and Geometry Dependency Studies

Wei Wu[1*], Ekaterina Ponizovskaya[1], Evgenia Kim[2], Alexander Bratkovsky[1], Zhaoning Yu[1], Qiangfei Xia[1], Xuema Li[1], Ron Shen[2], S.Y. Wang[1*] and R. S. Williams[1]

[1]Hewlett-Packard Laboratories, 1501 Page Mill Road, Palo Alto, California 94304
[2]University of California, Berkeley

Optical negative index meta-materials (NIMs) that exhibit unique refractive and focusing properties have recently become a focus of research worldwide. They have opened up new opportunities in nano-photonics and optical integration. We reported the first nanoimprint lithography (NIL)[1] fabricated NIMs at near-IR[2] and the first optical modulation of NIMs at near-IR[3]. However, they all had the (negative) minimum of the refractive index (*n*) located around the wavelength •=1.7 μm instead of the targeted 1.55 μm, which is the most attractive for optical communications. Here, we show results for a redesigned and newly fabricated "fishnet"-like NIM that exhibits the minimum of index *n* at 1.56 μm (Figure 1).

The NIMs we studied were based on the Ag/SiO_2/Ag "fishnet" tri-layer structure[4]. Theoretical design was done with the use of finite difference time domain method (FDTD). For the fabrication we have used nanoimprint lithography (NIL) and lift-off processes; the negative index character of the response has been confirmed by spectral ellipsometry. While the smallest feature in our structure was about 100 nm, which does not sound very challenging compared to other applications, our studies showed that NIM fabrication required very tight specifications on the dimensions, both lateral and vertical. For example, the wavelength spectral location (•) of the minimum of "*n*" changes by about 10 nm with either a 1 nm metal or a 0.7 nm dielectric layer thickness variation or a 3 nm line width variation (Figures 2 A-C). We also found that the non-vertical sidewall of the "fishnet" structure due to the lift-off process shifted the spectrum significantly (Figure 2D), and this geometrical issue has to be factored into the design. That was the main reason why our previous NIMs performance deviated from the goal of 1.55• m.

The biggest challenge in NIM fabrication came from holding the design specification over the entire NIL mold, which is made by EBL. On the other hand, the NIL process used to fabricate the NIM has great repeatability. We hit our design target by tuning the thicknesses of the stack to compensate for the feature size offsets of the NIL mold. Other issues, such as line edge roughness, and more details will also be presented.

1 S. Y. Chou, P. R. Krauss, and P. J. Renstrom, Science **272**, 85 (1996).
2 W. Wu, E. Kim, E. Ponizovskaya, Y. Liu, Z. Yu, N. Fang, Y. R. Shen, A. M. Bratkovsky, W. Tong, C. Sun, X. Zhang, S.-Y. Wang, and R. S. Williams, Applied Physics A: Materials Science and Processing **87**, 143 (2007).
3 E. Kim, W. Wu, E. Ponizovskaya, Z. Yu, A. M. Bratkovsky, S.-Y. Wang, R. S. Williams, and Y. R. Shen, Applied Physics Letters 91, 3105 (2007).
4 S. Zhang, W. J. Fan, K. J. Malloy, S. R. J. Brueck, N. C. Panoiu, and R. M. Osgood, Optics Express 13, 4922 (2005).

*Email: wei.wu@hp.com

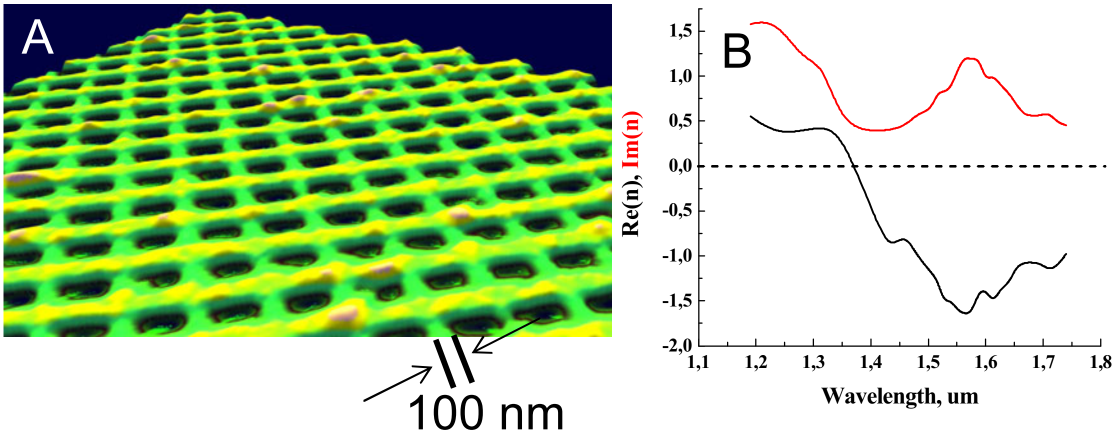

Figure 1. (A) An AFM image of the negative index meta-material. It has an Ag/SiO_2/Ag stack "fishnet" structure. (B) The refractive index, both real (black) and imaginary (red) parts, of the metamaterial shown in (A).

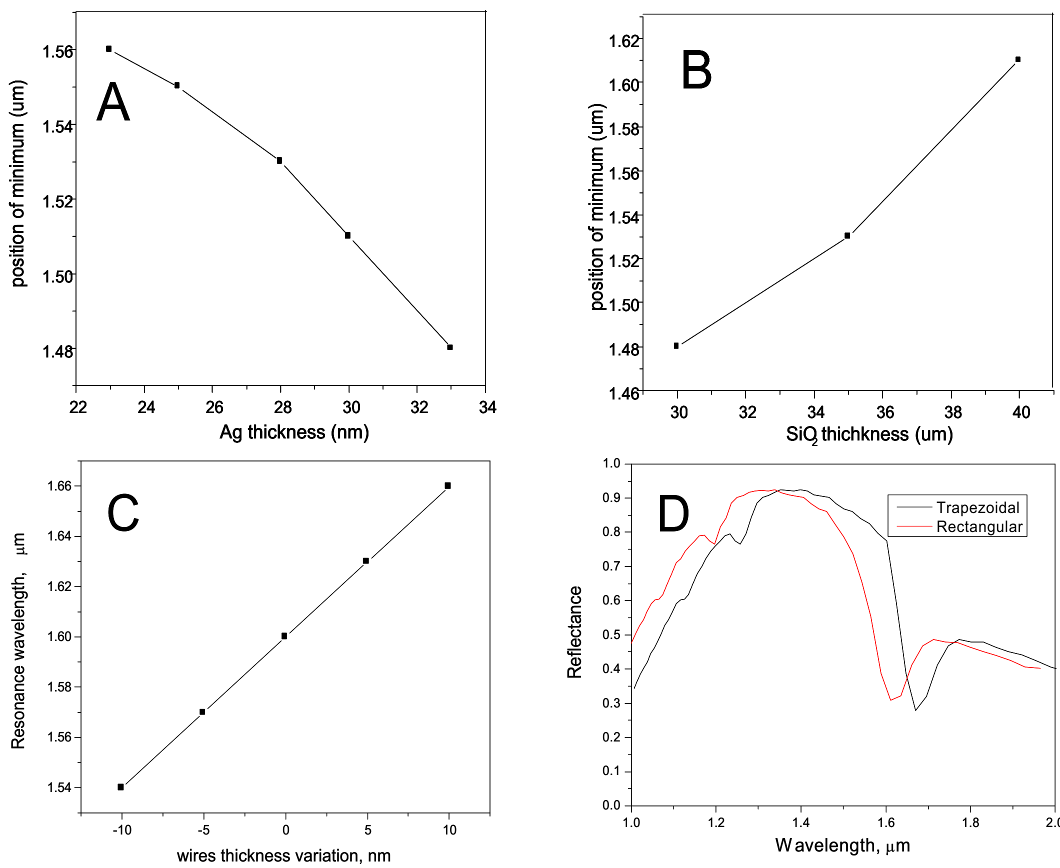

Figure 2. Theoretical results: The position of the minimum "*n*" corresponding to several geometric factors: (A) the Ag layer thicknesses, (B) the SiO_2 layer thickness, and (C) the line width. (D) Comparison of the "*n*" of the "fishnet" with a vertical sidewall (red) and a non-vertical sidewall (black). The non-vertical sidewall has an aspect ratio of 3:1, which is the same as our lift-off structures.