Supporting information for

Highly Directional Spaser Array for the Red Wavelength Region

Xiangeng Meng, [1,*,**] Jingjing Liu, [1,**] Alexander V. Kildishev, [1] Vladimir M. Shalaev [1,*]

[1]School of Electrical & Computer Engineering and Birck Nanotechnology Center, Purdue University, 1205 West State Street, West Lafayette, IN 47907–2057, USA

*Correspondence: mengxiangeng@gmail.com (X.M.); shalaev@purdue.edu (V.M.S.)

**These authors contributed equally to this work.

Numerical simulations

The calculation on optical transmission properties and local field distributions was performed using a finite element method using a commercial solver (Comsol Multiphysics v. 4.3b, Wave Optics Module). In the simulation, the refractive index of PVA is set as 1.52. The permittivity of the glass substrate is retrieved from ellipsometer software (W–VASE, J. A. Woollam Co., Inc.), as shown in Fig. S1. The dielectric constant of Ag is described by the Drude–Lorentz model with five Lorentz oscillators,[1]

$$\varepsilon = \varepsilon_1 - \frac{\omega_p^2}{\omega^2 + i\alpha_l \gamma_p \omega} + \sum_{m=1}^{5} \frac{f_m \omega_m^2}{\omega_m^2 - \omega^2 - i\gamma_m \omega}, \tag{3}$$

where ε_1 = 2.1485, ω_p = 9.1821 eV, γ_p = 0.0210 eV, α_l is a loss factor defined by the geometry and fabrication quality of nanostructured silver,[2] and the parameters of the Lorentz oscillators are shown in Table S1. A comparison of the dielectric constant with different loss factors is shown in Fig S2.

Table S1. Parameters of the Lorentz oscillators

m	ω_m, eV	f_m, eV	γ_m, eV
1	4.1980	0.1227	0.2659
2	4.5309	0.2167	0.4269
3	5.0094	0.2925	0.6929
4	5.7530	0.4305	1.1210
5	6.9104	0.4943	1.3410

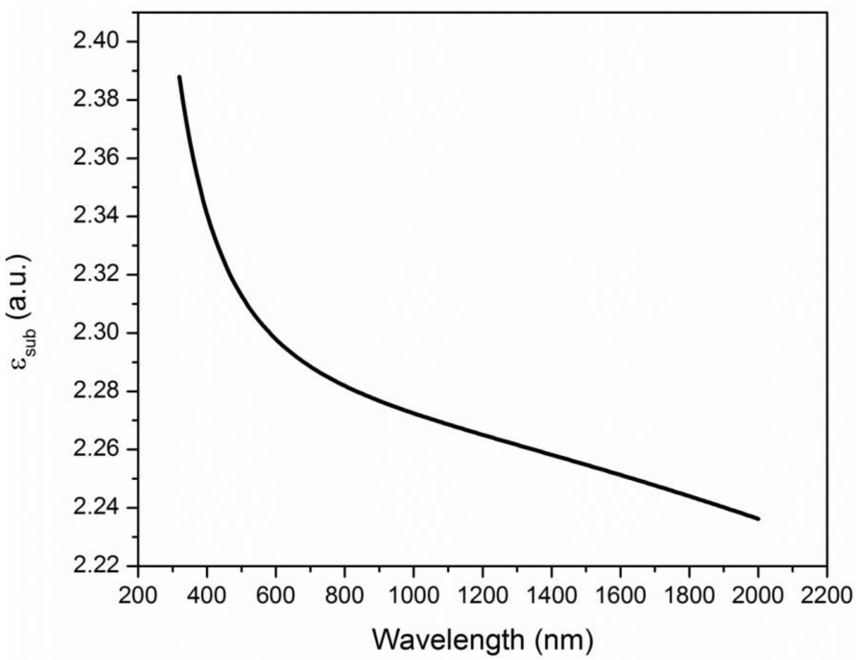

Figure S1. Permittivity of the glass substrate retrieved from spectroscopic ellipsometry.

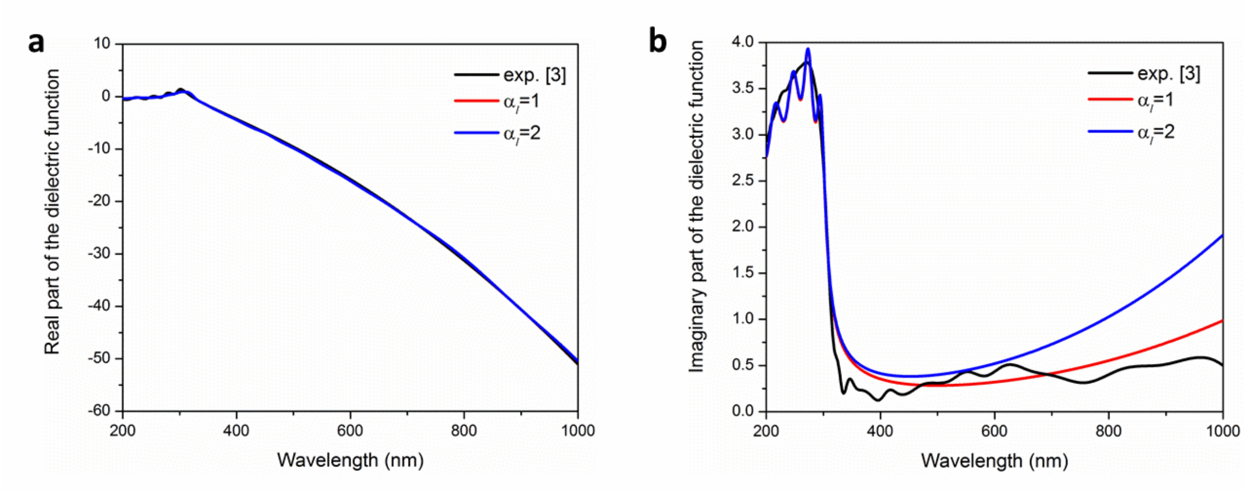

Figure S2. Comparison of the dielectric function of silver approximated with a Drude-Lorentz model of equation (3) taken with different loss factors and compared to the experimental data (Ref. 1): real (a) and imaginary part (b).

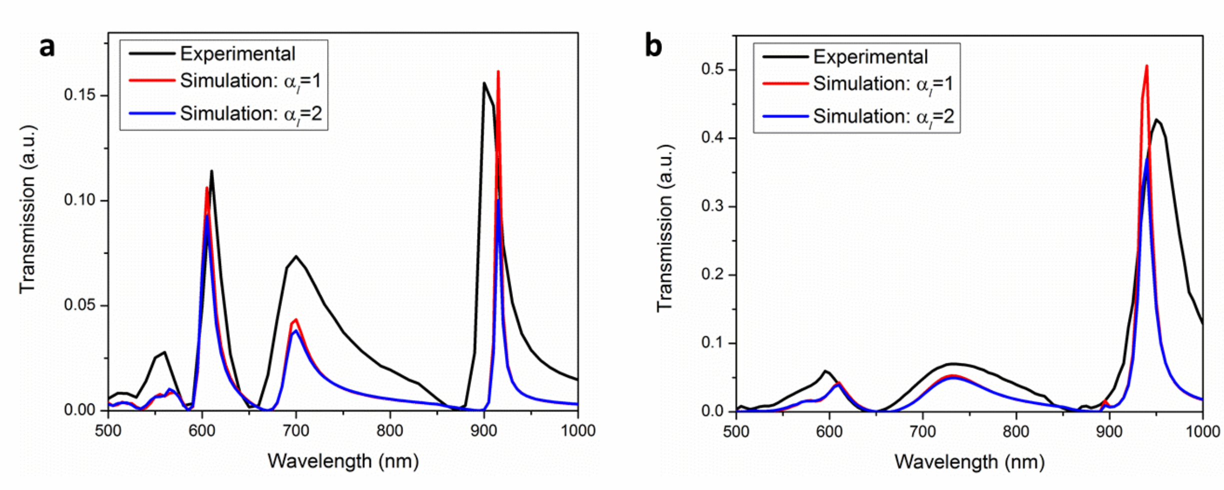

Figure S3. The transmission spectra of the empty (a) and PVA-covered (b) hole array calculated by taking α_l =1 (red curves) and 2 (blue curves) as well as the experimental results (black curves).

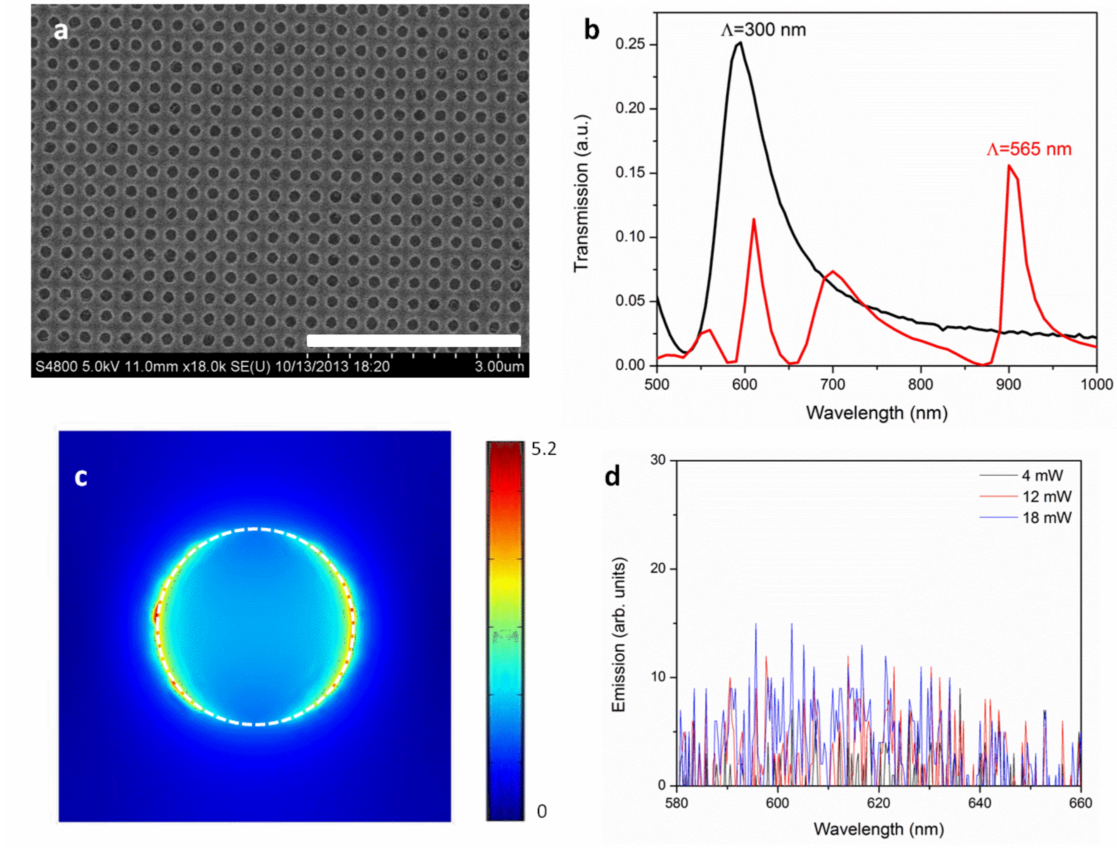

Figure S4. (a) SEM image of the periodic hole array showing plasmonic resonance at λ = 600 nm. Λ = 300 nm, d = 150 nm, t = 100 nm. The scale bar is 3 μm. (b) Transmission spectrum (black curve). The transmission of the holes with Λ = 565 nm shown in Fig. 1c is also included for comparison (red curve). (c) Electric field distribution at λ = 620 nm. The white circle indicates the position of the hole. (d) Evolution of the emission spectrum with the pump power, showing no lasing even at high pump power of 18 mW.

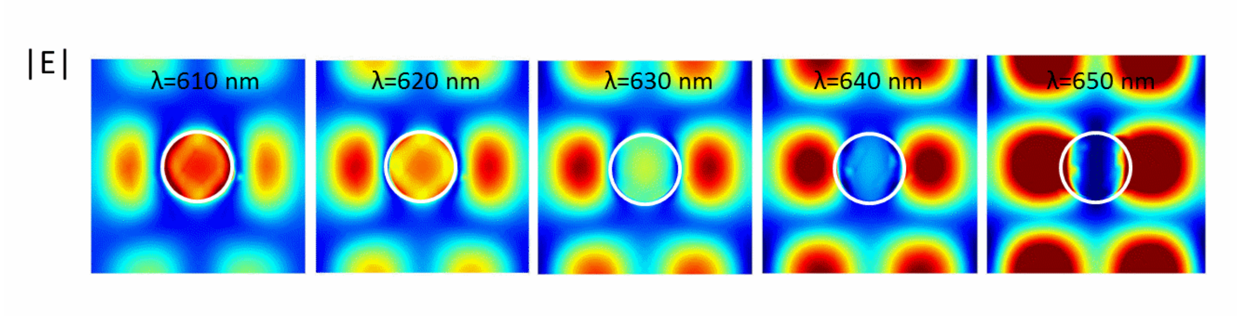

Figure S5. Electric field distributions on a unit cell of the hole array for λ = 610, 620, 630, 640, and 650 nm. The white circle indicates the position of the hole.

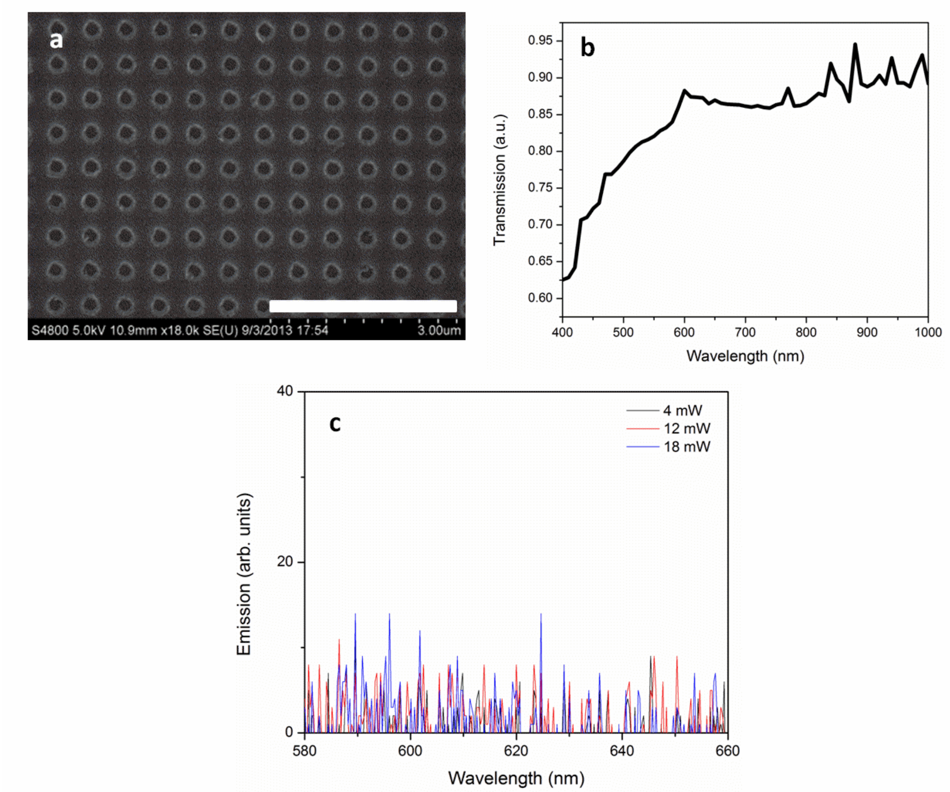

Figure S6. (a) SEM image of the periodic alumina holes. The scale bar is 3 μm. (b) Transmission spectrum of alumina holes, showing no obvious transmission resonance. (c) Evolution of the emission spectrum with the pump power, no signature of lasing was observed.

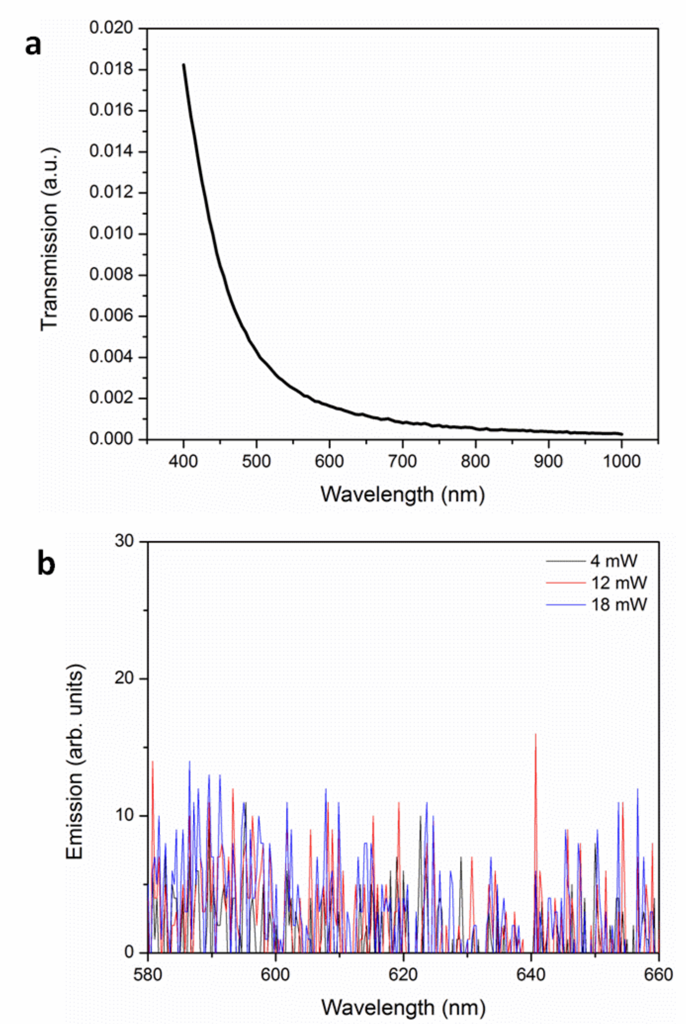

Figure S7. (a) Transmission spectrum of a 100 nm–thick silver thin film. (b) Evolution of the emission spectrum with the pump power for the sample composed of the silver thin film covered with R101–PVA thin film. No lasing was observed.

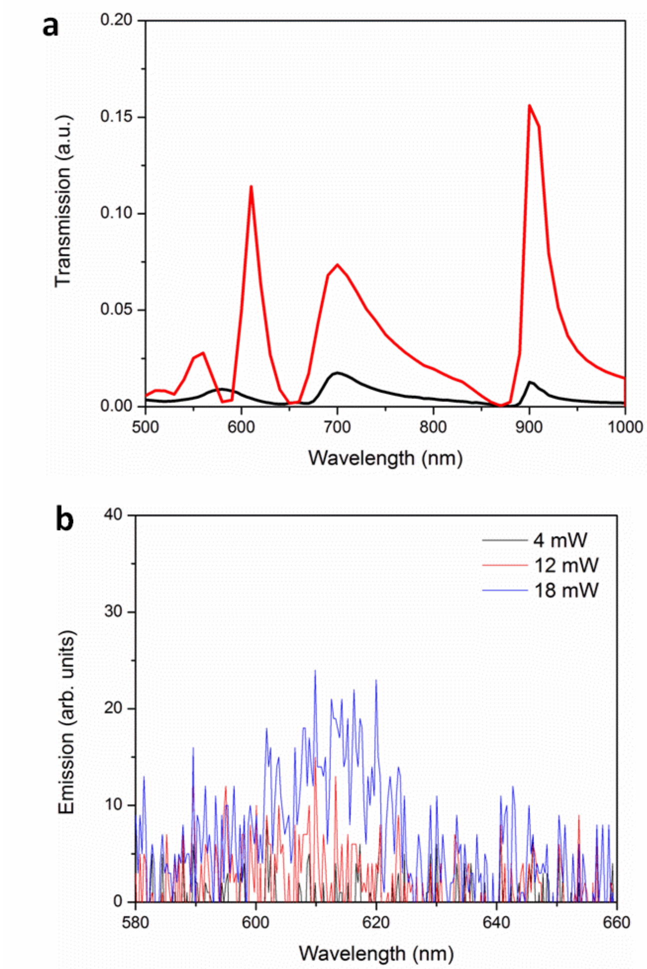

Figure S8. (a) Transmission spectrum of the periodic hole array with poor quality (black curve). The transmission of the holes shown in Fig. 1c is included for comparison (red curve). (b) Evolution of the emission spectrum with the pump power, showing only weak spontaneous emission signal.

References

[1] X. Ni, Z. Liu, and A. V. Kildishev (2010), "PhotonicsDB: Optical Constants," DOI: 10254/nanohub-r3692.10. http://nanohub.org/resources/3692.

[2] V. P; Drachev, U. K. Chettiar, A. V. Kildishev, H. K. Yuan, W. S. Cai, and V. M. Shalaev, Opt. Express 16, 1186-1195 (2008).

[3] P. B. Johnson, and R. W. Christy, Phys. Rev. B **6**, 4370-4379 (1972).