Appl. Phys. B (2015) 120:167–170
DOI 10.1007/s00340-015-6120-2

Applied Physics B
Lasers and Optics

Broadband field enhancement of THz electromagnetic wave by surface-textured micron PVDF cylinders

Xinxin Li[1] · Xuan Liu[1] · Luoning Zhang[1] · Jing Zhou[1] · Dahe Liu[1]

Received: 13 January 2015 / Accepted: 23 April 2015 / Published online: 1 May 2015

Abstract A cylindrical dimmer system is proposed to realize broadband field enhancement for terahertz (THz) electromagnetic wave. A surface-textured crescent-shaped cylinder is proposed to red-shift the absorption spectrum comparing to the traditional crescent-shaped cylinder based on the concept of spoof surface plasmons. Such cylinders made of ferroelectric polyvinylidene fluoride can realize the electromagnetic wave harvesting at terahertz frequencies with a broadband and huge absorption cross section. Two such cylinders in close proximity could achieve considerable electromagnetic field enhancement and field confinement in the gap, which could be applied in THz molecules detection, toxic chemical sensing, and safety screening and could break the detection binding that limits the molecules <100 nm.

1 Introduction

For a long time, plasmonics has attracted a great deal of attention due to the possibility of subwavelength confinement and concomitant enhancement of the electromagnetic (EM) field at metal–dielectric interfaces [1–5]. One typical structure is the crescent-shaped metal nanostructure [6–10] which could realize nanoscale optical field localization and enhancement by the resonantly focused plasmons. Taking the advantage of transformation optics, Pendry et al. demonstrated that a metal cylinder of crescent-shaped cross section with kissing crescent tips could achieve broadband harvesting of light in the visible spectrum [11, 12]. As subwavelength confinement of surface plasmons relies on the penetration of the EM field into the metal, its usage is inevitably limited to visible or near-infrared frequencies. To explore the wave harvesting property in lower frequencies, we propose a surface-textured crescent-shaped cylinder in this paper, which could efficiently red-shift the absorption spectrum comparing to the traditional crescent-shaped cylinder with the help of the spoof surface plasmon excitation [13–15]. With the ferroelectric polyvinylidene fluoride (PVDF) [16, 17], the dimmer system of such cylinders could achieve considerable electromagnetic field enhancement and confinement at terahertz (THz) frequencies. This could be applied in big molecules detection and could break the detection binding that limits the molecules <100 nm [18].

✉ Jing Zhou
jzhou@bnu.edu.cn

[1] Applied Optics Beijing Area Major Laboratory, Department of Physics, Beijing Normal University, Beijing 100875, People's Republic of China

2 Theoretical analyses

The proposed dimmer system consists of two surface-textured crescent-shaped micron cylinders. The structure of the cylinder is a mathematical conformal transformation of a thin infinite slab with periodic surface textures shown in Fig. 1. The referred conformal transformation is $z' = \frac{g^2}{z^*}$, where z and z' are the usual complex number notations; the subscript * stands for complex conjugate; g is an arbitrary constant. The surface-textured slab supports spoof surface plasmons which can couple with a dipole source and transport the energy to infinity. The spectrum of the spoof surface plasmons is continuous and broadband [13–15, 18, 19] because there is no dimensional confinement in the propagation direction.

The three planes of $x = x_o$, $x = x_m$, and $x = x_i$ in Fig. 1a are transformed into three cylinders in Fig. 1b with the

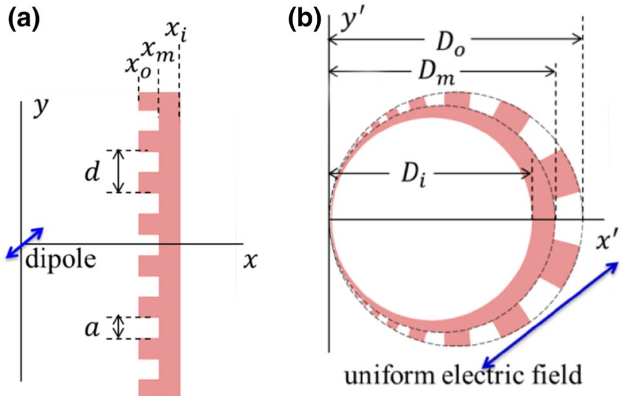

Fig. 1 **a** A slab textured by *rectangular* grooves with a dipole source near the textured surface. **b** The proposed crescent-shaped cylinder from the conformal transformation of the structure in (**a**)

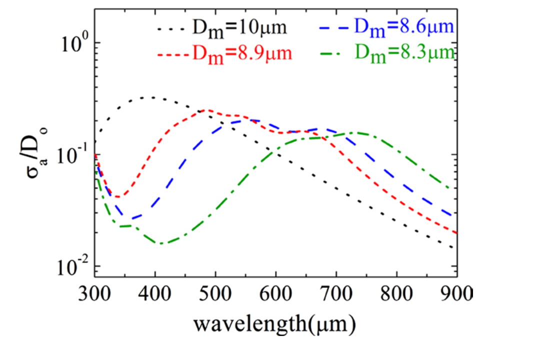

Fig. 2 Normalized absorption cross section, σ_a/D_0, as a function of wavelength for the cylinders with $f = 0.5$, $D_o = 10$ µm, $D_i = 8.0$ µm, and $D_m = 8.3$, 8.6, 8.9, 10 µm. The incident wave is a TM-polarized plane wave propagating along the y' axis

diameters of $D_o = \frac{g^2}{x_o}$, $D_m = \frac{g^2}{x_m}$, and$D_i = \frac{g^2}{x_i}$, respectively. Hence, the resulted structure is a crescent-shaped cylinder with groove-like outer surface. According to the transformation optics, the relevant permittivity ε' and permeability μ' in the cylinder frame are the same as the original ε and μ in the slab frame. The dipole source in Fig. 1a is transformed to the incident uniform electric field in Fig. 1b, which could excite surface plasmons at the textured surface of the cylinder [20, 21].

Just as the spoof surface plasmons could propagate along the surface of the thin slab to infinity, the spoof surface plasmon modes in the cylinder in Fig. 1b accordingly propagate around the singularity point. Thus, the electromagnetic wave will be harvested around the tip by the balance of the energy accumulation and the lossy. Using the PVDF proposed to excite low-frequency plasmons [16, 17], this cylinder structure could achieve broadband harvesting of electromagnetic wave at THz frequencies.

The properties of the proposed structure can be analyzed by its normalized absorption spectrum. In the quasi-static approximation, the energy pumped into the spoof surface plasmons propagating along the textured surface of the crescent cylinder can be evaluated by the power absorbed from the uniform electric field incident on the crescent cylinder [11, 12]. The absorbed power P can be calculated by the Ohmic loss of the crescent cylinder. And the absorbed power P normalized by the incoming flux P_{in} is the absorption cross section $\sigma_a = P/P_{\text{in}}$, where $P_{\text{in}} = \varepsilon_0 c E_0^2/2$, c is the light speed, and E_0 the electric field amplitude of the incident wave.

3 Numerical simulations

To verify the property of the proposed structure, we made full-wave simulations using the finite element method with the software COMSOL Multiphysics. The PVDF material used in the calculation is a ferroelectric semicrystalline polymer described by $\varepsilon_{\text{PVDF}}(\omega) = \varepsilon_{\text{opt}} + \frac{(\varepsilon_{\text{dc}} - \varepsilon_{\text{opt}})\omega_{\text{TO}}^2}{\omega_{\text{TO}}^2 - \omega^2 + i\gamma\omega}$ with $\varepsilon_{\text{opt}} = 2.0$, $\varepsilon_{\text{dc}} = 50$, $\omega_{\text{TO}} = 0.3$ THz, and $\gamma = 0.1$ THz [17]. The real part of the dielectric constant of PVDF is negative in the THz region. In Fig. 1a, the period and the open width of the groove are described as d and a. It is known that the asymptote frequency of the spoof surface plasmons is mainly determined by the optical depth of the groove, $\omega_a = \pi c/(2hn_g)$ [13, 15]. n_g is the refractive index of the media filled in the grooves. h represents the depth of the groove, which is $x_m - x_0$ in Fig. 1a. Thus, the frequency of the spoof surface plasmons is independent of the filling ratio a/d. Without loss generality, we set $a/d = 0.5$ and $n_g = 1$ in the following calculation. Theoretically, the number of the grooves in the outside surface of the crescent-shaped cylinder should be infinity, and the groove depth becomes smaller and smaller when approaching to the point of singularity. The simulations show that the number of grooves does not have to be infinity, the optimized number is $N = 19$, which could preserve the light harvesting property very well. Since the PVDF supporting surface plasma at the wavelength ranging from 100 to 700 µm [16], the values of D_o, D_i, and D_m should be in the order of micron. Keeping $D_o = 10$ µm and $D_i = 8.0$ µm unchanged, we calculated the normalized absorption spectrums for $D_m = 8.3$, 8.6, 8.9 µm. The calculated results are presented in Fig. 2. The absorption spectrum for $D_m = 10$ µm, corresponding to the crescent-shaped cylinder without outer surface-textured, is presented (black dots) for comparison.

It can be seen from Fig. 2 that the absorption spectrum red-shifts gradually when the grooves get deeper. This means that the proposed surface-textured structure can move the spectrum to the lower frequencies efficiently. Based on these results, it can be expected that the red-shifted spectrum with wider band could be achieved by a cylinder with

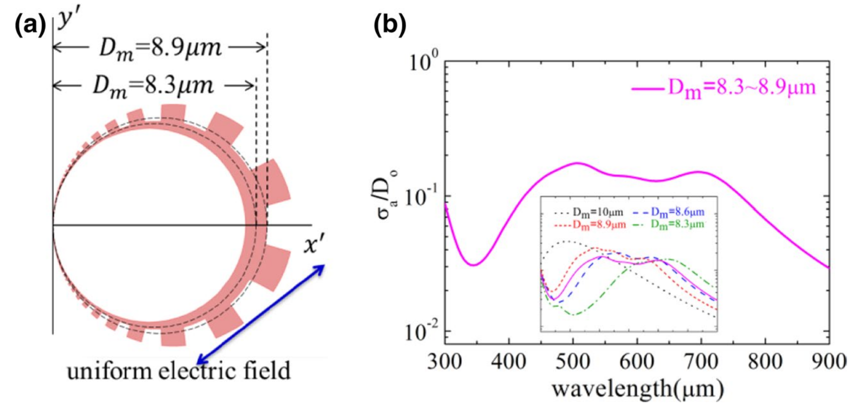

Fig. 3 **a** Crescent-shaped cylinder with outer surface textured by grooves of seven different depths, the corresponding D_m changes from 8.9 to 8.3 µm with step of −0.1 µm repeatedly. **b** The *solid pink* line shows the normalized absorption cross section, σ_a/D_0, as a function of wavelength for the structure in (**a**), while the *inset* shows this *solid pink line* together with those *lines* presented in Fig. 2 for comparison

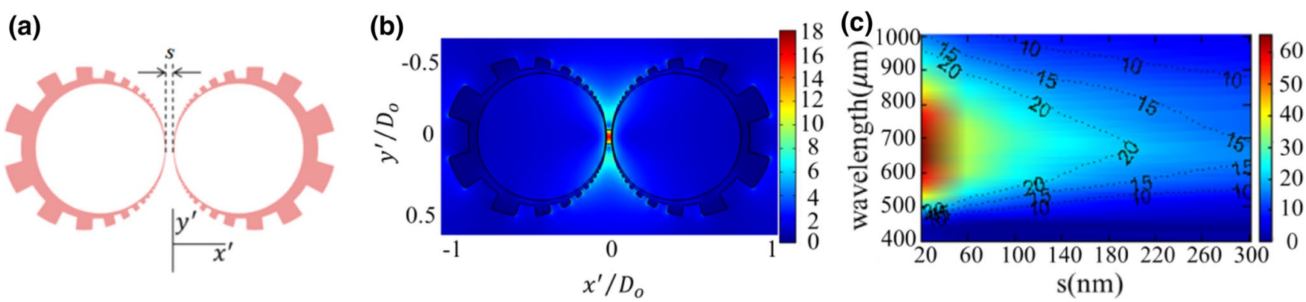

Fig. 4 **a** Dimmer consisting of two surface-textured cylinders separated by a gap width "*s*." **b** The distribution of electric field intensity normalized to the incident wave for $s = 300$ nm at the wavelength of 650 µm. **c** The maximum normalized field intensity as a function of the gap width and wavelength

grooves of multiple different depths. Thus, we designed the cylinder structure with different groove depths as shown in Fig. 3a, where the values of D_m change from 8.9 to 8.3 µm with the step of −0.1 µm repeatedly. Still setting $N = 19$, $D_o = 10$ µm, and $D_i = 8$ µm, the calculated normalized absorption spectrum is shown in Fig. 3b. The inset of Fig. 3b shows the current absorption spectrum together with those presented in Fig. 2 for comparison. Just as predicted, the current absorption spectrum is red-shifted with a wider band. Moreover, the value is quite large over the whole band.

If we put two such cylinders together, the interaction between them can be used to achieve the field enhancement (FE). The cylindrical dimmer consisted of the surface-textured cylinders is shown in Fig. 4a. Since the size of the proposed cylinders is in micron, the quantum mechanical effects such as electron tunnelling and screening do not have to be taken into account [22, 23].

The simulations show that such a dimmer system could realize FE at the central gap. In the calculation, the incident wave is a TM-polarized plane wave propagating along the y' direction. The properties are shown in Fig. 4. The geometric parameters are $D_o = 10$ µm, $D_i = 8$ µm, $D_m = 8.6$ µm, and $N = 19$. Figure 4b is the distribution of electric field intensity normalized to the incident wave for $s = 300$ nm at the wavelength of 650 µm. The FE in the central gap of the cylinders can be seen clearly. And the maximum normalized field intensity is 18. Figure 4c shows the maximum normalized field intensity as a function of s and wavelength, where s varies from 20 to 300 nm and the wavelength changes from 400 to 1000 µm. It is obvious that the proposed cylinder dimmer could act as an efficient energy collector with broadband harvesting of electromagnetic wave at THz frequencies. The field enhancement in the central gap decreases when the cylinders get farther. Nevertheless, the maximum normalized FE is still more than 15 at a rather broadband when the gap width increases to $s = 150$ nm. This proposed cylinder dimmer could be used to detect the nanomolecules in THz frequencies [16].

In practical applications, the fabrication of the proposed cylinder might be a challenge because its surface is textured with nanoscaled grooves. The depth and the width of the minimum groove are several tens of nanometers and several hundreds of nanometers, respectively. But it is reported that the resolution of the electron beam lithography in the conventional polymethyl methacrylate (PMMA) could be pushed below 10 nm for isolated features, and the arrays of periodic structures can be fabricated at a pitch of 30 nm [24]. Therefore, we believe it is possible to realize the proposed PVDF structure in the future.

4 Conclusion

Based on the transformation optics technique, a broadband electromagnetic field enhancement of THz electromagnetic wave is realized in the central gap of a dimmer consisting of two surface-textured cylinders. This will open perspectives for applications in THz spectroscopy, biological detection, chemical sensors, and environmental sensing.

Acknowledgments The authors thank the National Natural Science Foundation of China (Grant No. 61275130) for financial support. The authors also thank Dr. Jun Zheng and Prof. Zhengming Sheng in Shanghai Jiaotong University for their help in numerical simulations.

References

1. W.L. Barnes, A. Dereux, T.W. Ebbesen, Nature **424**, 824–830 (2003)
2. E. Ozbay, Science **311**, 189–193 (2006)
3. S.A. Maier, *Plasmonics: Fundamentals and Applications* (Springer, New York, 2007)
4. U. Kreibig, M. Vollmer, *Optical Properties of Metal Clusters* (Springer, Berlin, 1995)
5. Miguel Navarro-Cia, Stefan A. Maier, ACS Nano **6**, 3537–3544 (2012)
6. Y. Lu, G. Liu, J. Kim, Y. Mejia, L. Lee, Nano Lett. **5**(1), 119–124 (2005)
7. J. He, C. Fan, J. Wang, P. Ding, G. Cai, Y. Cheng, J. Opt. **15**(7), 025007 (2013)
8. B. Ross, L. Lee, Nanotechnology **19**(6), 275201 (2008)
9. L. Feng, D. Orden, M. Abashin, Q. Wang, Opt. Express **17**(6), 4824–4832 (2009)
10. L.Y. Wu, B. Ross, L. Lee, Nano Lett. **9**(5), 1956–1961 (2009)
11. A. Aubry et al., Nano Lett. **10**(7), 2574–2579 (2010)
12. A. Aubry et al., Phys. Rev. B **82**(12), 125430 (2010)
13. F.J. García-Vidal, L. Martín-Moreno, J.B. Pendry, J. Opt. A Pure Appl. Opt. **7**, S97–S101 (2005)
14. S.A. Maier et al., Phys. Rev. Lett. **97**(17), 176805 (2006)
15. A. Pors et al., Phys. Rev. Lett. **108**(22), 223–905 (2012)
16. A. Hassani, M. Skorobogatly, Opt. Express **16**(25), 20206–20214 (2008)
17. T. Hidaka et al., J. Light. Technol. **23**(8), 2469–2473 (2005)
18. F. Yang, J. Sambles, G.W. Bradberry, Phys. Rev. B **44**(11), 5855–5872 (1991)
19. G.J. Kovacs, G.D. Scott, Phys. Rev. B **16**(4), 1297–1311 (1977)
20. D. Schurig, J.B. Pendry, D.R. Smith, Opt. Express **14**(21), 9794–9804 (2006)
21. H. Chen, C.T. Chan, P. Sheng, Nat. Mater. **9**, 387–396 (2010)
22. L. Mao et al., Appl. Phys. Lett. **94**, 243102 (2009)
23. P. Song, P. Nordlander, S. Gao, J. Chem. Phys. **134**, 074701 (2011)
24. C. Vieu et al., Appl. Surf. Sci. **164**, 111–117 (2000)