Infrared Physics & Technology xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Impact of optical antenna and plasmonics on infrared imagers

Alireza Bonakdar, Hooman Mohseni *

Bio-Inspired Sensors and Optoelectronics Lab (BISOL), EECS Department, Northwestern University, Evanston, IL 60208, United States

HIGHLIGHTS

- ▶ Infrared detectors operating in the mid and long-infrared suffer from weak light-matter interaction.
- ▶ We developed optical antenna that enhance light-matter interaction, leading to enhanced responsivity and detectivity.
- ▶ We demonstrated long-IR detectors that show enhanced light-matter interaction experimentally.
- ▶ The measured performance shows good agreement to our 3D numerical modeling results.
- ▶ We have also demonstrated other IR devices that benefit from optical antenna with significant enhancements.

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Infrared
QWIP
Specific detectivity
Optical antenna
Surface plasmonics

ABSTRACT

The advent of nanophotonics allows devising and fabricating optical antenna as the advanced optical structures that can enhance light–matter interaction in quantum structures such as quantum wells. Improving infrared photodetector performance is discussed theoretically in this paper. We also investigate our recent demonstration of optical antenna integrated on quantum well infrared photodetector which improves the performance of the detector as can be evidence in responsivity of the detector.

1. Introduction

Infrared (IR) detection is an important field of research with a broad range of applications such as (bio) molecular and chemical sensing [1–4], astronomy [5–7], night vision [8] and short range communication [9]. IR imagers have been subjected to heavy research within last decade in order to improve their operational parameters such as temperature stability [10,11], specific detectivity (D^*) [12,13] and quantum efficiency (QE) [14]. Specific detectivity is an important figure of merit to analyze and compare normalized signal to noise performance of IR detectors [15]. Since specific detectivity is directly proportional to the ratio of QE to dark current, it can be optimized by increasing QE and decreasing dark current. QE is directly related to how strongly infrared light interacts with the electronic states of the detecting region of the device. Devising advanced photonic structure at the vicinity of the quantum structure can increase light–matter interaction [16–23]. Dark current in the device can be controlled by enhancing the design of heterostructure [24,25], quality of device fabrication [26–28]. Unfortunately improving imperfections due to material quality beyond what is achievable today is very challenging and time consuming process. This is partly due to lack of accurate models describing the growth process, and hence limited ability to predict how to change the many parameters involved in the crystal growth. Reducing device size as an additional step is a promising technique to decrease noise current [19], while it is traditionally limited by the diffraction limit – which is rather large for mid and long wavelength regions.

In this paper, we show how nanophotonic structure can improve quantum efficiency and reduce dark current of IR photodetectors beyond the current state-of-the-art. While conventional photonic structures are known for controlling and enhancing detectivity by focusing and trapping light at detection site of the device [21–23], they suffer from fundamental diffraction limit [29] which restrict their functionality to improve IR detectors. However, nanophotonics as a new branch of photonics with the capability of compressing light into deep subwavelength regions [30,31] is a promising approach to enhance light–matter interaction [32–34]. Optical antenna as a nanophotonic structure can convert far field detected light into near field optical mode by means of surface plasmon polariton (SPP) [35]. SPP is an optical mode at the interface of metal and dielectric which is coupled with free electrons on the metal side [30]. Far field to near field conversion by

* Corresponding author.
E-mail address: hmohseni@northwestern.edu (H. Mohseni).

1350-4495/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.infrared.2012.12.029

optical antenna can significantly improve device performance as the detecting site of the device is within the near field region.

This paper is organized as follows: (1) we present a theoretical framework in order to explain the effect of optical antenna to enhance the quantum efficiency and reducing dark current. (2) Simulation and experimental results of a surface plasmon enhanced quantum well infrared photodetector (QWIP) is presented and discussed. Metallic nanohole array is used as the optical antenna which can couple far field IR light into near field intense light in the vicinity of detecting region of QWIP. (3) We conclude and summarize the benefits of optical antenna for improving the performance of IR detectors.

2. Theoretical framework

Infrared light is detected and converted to electric signal when an electron in a quantum structure absorbs photon and contributes to the electric current. As a result of light absorption, electron transits from an initial state to a final state with their energy difference are equal to the photon energy. Beside energy conservation, the overall momentum should be also conserved. Fig. 1 shows schematically the dispersion diagram of different particles. Since, photon cannot provide momentum difference between initial and final electronic states; only band edge absorption – in direct gap material – is significant where electronic states have small momentum. However, momentum of SPP as a result of photon – free electron coupling is much larger than the initial photon [30]. Thus, the interaction of SPP and electronic states in the quantum structure of the detector can be much more efficient.

Since SPP has larger momentum (smaller wavelength) compared with photon, it can squeeze and compress light into sub wavelength scale. Based on Fourier optics, the ability to confine light into a nanoscale region comes from the fact that SPP wave packet composed of high wave vector to shaping SPP mode in nanoscale regions [36]. As a result of such compressing, electric field of EM wave is enhanced and the overlap integral between electron wave function and optical mode increases [34,37]. Squeezing optical mode into subwavelength scale has profound effects for detectors with subwavelength scale of dimensions as electronic states are limited to very tiny space and the overlap function of optical mode and electronic states cannot be significant. However, optical antenna can elaborate the mode shape of SPP to increase the overlap of optical energy and electronic states to increase the light absorption at detection site. In general, confining light along the dimension in which, electronic states are confined can effectively increase the optical absorption. For example, electronic states are confined along the growth direction of quantum wells of quantum well infrared photodetectors (QWIP). Squeezing light along the same direction can enhance optical absorption and consequently the performance of QWIP as will be discussed in more details in the next section.

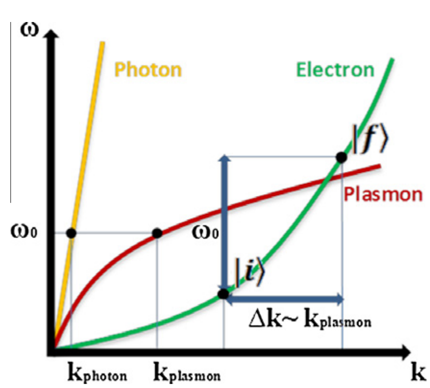

Fig. 1. Comparing momentum of different particles. Dispersion diagram of different particles with their relative wavevectors. The electronic transition is also shown along the parabolic dispersion of electron in a semiconductor.

Based on Fermi golden rule, linear optical absorption is directly related to electric field intensity and overlap integral between optical mode and electronic states [38]:

$$R_{Abs} = \frac{2\pi}{h}\langle f|H_{int}|i\rangle^2 \delta(E_f - E_i - h_\omega)$$

with interaction operator $H_{int} = \frac{ie}{2m_0\omega} F \cdot p$ where F and p are electric vector of EM wave and electron momentum, respectively. Thus, SPP can enhance light absorption and subsequently QE by confining light into subwavelength active region of IR detector. Higher QE results in higher current responsivity as $R_I = \frac{q\lambda}{hc}\eta$ where η is QE and λ is free space optical wavelength. Since, optical antenna can couple far field light with small momentum into near field optical mode with large momentum and intense intensity [35], it can increase the rate of light absorption.

Light confinement has another importance consequence: shrinking device size in order to reduce noise current. The level of noise current highly depends on the quality of fabrication [27]. However, there is a fundamental limit in noise level reduction coming from quantum nature of electronic signal [15]. As a result, the only way to reduce noise current further is to reducing device size. In conventional photonic devices, reduction in device size results in degradation of QE specifically beyond diffraction limit. However, nanophotonics has the capability to squeeze light and reduce device size without affecting detector's performance with a moderate loss.

Specific detectivity is defined as the ratio of current responsivity to noise power: $D^* = \frac{R_I\sqrt{A\Delta f}}{\langle i_n^2\rangle}$ where $\langle i_n^2\rangle$ is noise power, and A and Δf are detector area and bandwidth. Optical antenna can address both enhancing current responsivity and noise reduction and as a result, enhancing specific detectivity of the device.

This idea could be viewed within the traditional microwave theory. Since impedance of an electric dipole is very different from the vacuum impedance, far field IR power cannot efficiently reach to electric dipole. Based on electric circuit theory, the maximum power reaches to the load is half the power of feeder with the impedance matching condition in which the load impedance should be equal to feed impedance. Based on nanocircuit theory, optical antenna can be modeled as an adjustable impedance to compensate the mismatch between load and vacuum impedance [35].

3. Simulation and experimental results

In this section we discuss our recent research on incorporating optical antenna/coupler with QWIP [19]. QWIP detector has response at 8 μm so FDTD simulation is used to design an optical antenna with the response matches to QWIP resonant response. The

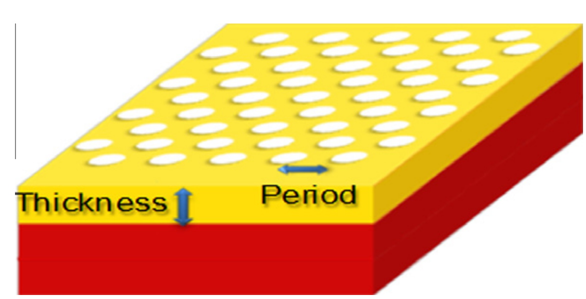

Fig. 2. Structure used to simulate the response of optical antenna on top of QWIP.

Please cite this article in press as: A. Bonakdar, H. Mohseni, Impact of optical antenna and plasmonics on infrared imagers, Infrared Phys. Technol. (2013), http://dx.doi.org/10.1016/j.infrared.2012.12.029

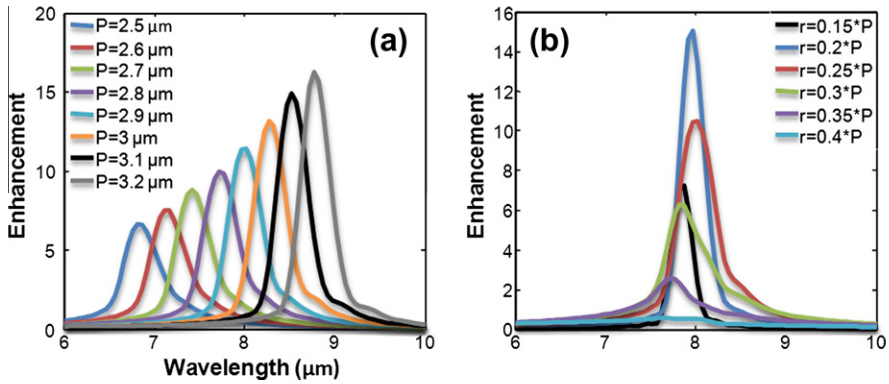

Fig. 3. Simulation results for optimization. The average Ez-intensity enhancement spectrum (a) for different period of hole array and (b) different hole radius

schematic of optical antenna used in simulation is shown in Fig. 2. It is composed of nanohole array perforated on a gold thin film on top of the QWIP. We used commercial FDTD software to simulate the response of optical antenna by exciting the system using IR broadband plane wave source with linear polarization. Assuming periodic boundary conditions for lateral directions (x and y) and perfect matched layer (PML) for perpendicular direction (z), simulations are performed by using nonuniform mesh technique to reduce computational load and increase accuracy.

Although QWIP is composed of many layers with different refractive indices, we assume index of 3 for whole QWIP structure. Such an approximation is valid since the difference of refractive index is less than 10 percent along different layers. Nanohole array can provide extra momentum to excite surface plasmon at the gold/air and gold/QWIP interfaces. Surface plasmon resonant wavelength is highly dependent on the periodicity of nanohole array. In order to optimize the structure, we performed a series of simulations by sweeping over period of nanohole array. Since electric field with polarization along the growth direction (z direction in simulation) can be absorbed by QWIP, the electric field along z direction is averaged over QWIP detecting volume and divided by the averaged electric field intensity of QWIP without any SPP coupler. The resulted quantity shows the enhancement of the electric field upon using optical antenna. As shown in Fig. 3a, the electric field intensity along z direction depends on the periodicity of the nanohole array. By optimizing the structure, more than 15 times enhancement can be achieved as shown in Fig. 3b where the enhancement spectrum for different hole's radius is simulated.

In experiment, optical antenna is fabricated on QWIP by depositing thin film of gold (50 nm) on the surface of the detector using e-beam evaporator. Nanoholes are fabricated on the metal using focus ion beam milling (FIB). Fig. 4a and b are SEM images of the device after processing. Using Fourier transform infrared spectroscopy, we measured the spectrum response of our plasmonic enhanced QWIP. Experimental and simulation results well match as shown in Fig. 4c. The achieved responsivity for the specific QWIP thickness (500 nm) in our experiment is much higher compared with the case without using optical antenna. The reason can be ex-

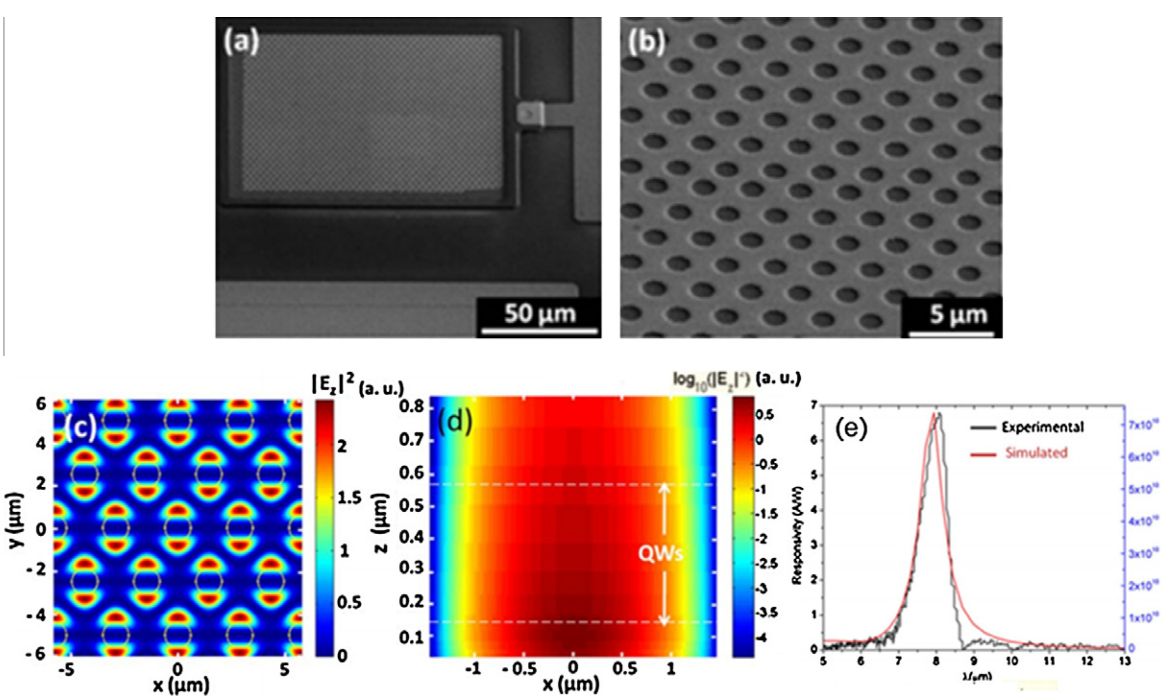

Fig. 4. Simulation and experimental results (a and b) SEM images of plasmonic enhanced QWIP structure (top view). (c) Ez intensity profile under the holes array. Circular rings are showing the position of the holes. (d) The vertical view of Ez intensity profile which shows the position of QWIP too. (e) The measured responsivity and detectivity of the device. Simulation and experimental results are well matched.

Please cite this article in press as: A. Bonakdar, H. Mohseni, Impact of optical antenna and plasmonics on infrared imagers, Infrared Phys. Technol. (2013), http://dx.doi.org/10.1016/j.infrared.2012.12.029

plained by inspecting Fig. 4d and e as they show simulated Ez intensity profile in the lateral direction beneath the metal layer and perpendicular direction, respectively.

4. conclusions

In conclusion, we discussed the theoretical reasons of enhancement of light absorption as a result of utilizing optical antenna. We experimentally showed that optical antenna can improve the performance of QWIP as demonstrated in responsivity of the detector.

Acknowledgements

This work is partly supported by ARO project # W911NF-11-1-0390, and NSF EAGER project # ECCS-1206155. Authors would also like to acknowledge the use of Northwestern's high-performance computing facility Quest.

References

[1] B. Stuart, Infrared spectroscopy, in: Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, Inc., 2000.
[2] F.L. Martin, J.G. Kelly, V. Llabjani, P.L. Martin-Hirsch, I.I. Patel, J. Trevisan, N.J. Fullwood, M.J. Walsh, Distinguishing cell types or populations based on the computational analysis of their infrared spectra, Nat. Protoc. 5 (2010) 1748–1760.
[3] A. Schliesser, M. Brehm, F. Keilmann, D. van der Weide, Frequency-comb infrared spectrometer for rapid, remote chemical sensing, Opt. Express 13 (2005) 9029–9038.
[4] B.L. Carter, E. Shaw, J.T. Olesberg, W.K. Chan, T.C. Hasenberg, M.E. Flatte, High detectivity GaInAsSb pin infrared photodetector for blood glucose sensing, Electron. Lett. 36 (2000) 1301–1303.
[5] D. Jean-Michel, B. Jacob, K. Eliza Miller-Ricci, K.B. Zachory, C. David, I. Jonathan, F. Jonathan, J.B. Christopher, N. Philip, Observational evidence for a metal-rich atmosphere on the super-earth GJ1214b, Astrophys. J. Lett. 731 (2011) L40.
[6] D.W. McCarthy, L.A. Lebofsky, M.L. Higgins, N.R. Lebofsky, The James Webb Space Telescope's Near-Infrared Camera (NIRCam): Making Models Building Understanding, vol. 443, Astronomical Soc Pacific, San Francisco, 2011.
[7] D. Stark, Astronomy: searching for the cosmic dawn, Nature 489 (2012) 370–371.
[8] S. Hao, W. Cheng, W. Boliang, Night vision pedestrian detection using a forward-looking infrared camera, in multi-platform/multi-sensor remote sensing and mapping (M2RSM), in: International Workshop on, 2011, p. 1–4.
[9] J.C. Campbell, Recent advances in telecommunications avalanche photodiodes, J. Lightwave Technol. 25 (Jan 2007) 109–121.
[10] H. Mohseni, M. Razeghi, Long-wavelength type-II photodiodes operating at room temperature, IEEE Photon. Technol. Lett. 13 (May 2001) 517–519.
[11] P.L. Voss, K.G. Koprulu, S.K. Choi, S. Dugan, P. Kumar, 14 MHz rate photon counting with room temperature InGaAs/InP avalanche photodiodes, J. Modern Opt. 51 (2004) 1369–1379.
[12] O.G. Memis, A. Katsnelson, S.-C. Kong, H. Mohseni, M. Yan, S. Zhang, T. Hossain, N. Jin, I. Adesida, A photon detector with very high gain at low bias and at room temperature, Appl. Phys. Lett. 91 (2007).
[13] J. Kohoutek, I.Y.L. Wan, O.G. Memis, H. Mohseni, An opto-electro-mechanical infrared photon detector with high internal gain at room temperature, Opt. Express 17 (2009) 14458–14465.
[14] O.G. Memis, J. Kohoutek, W. Wu, R.M. Gelfand, H. Mohseni, Signal-to-noise performance of a short-wave infrared nanoinjection imager, Opt. Lett. 35 (Aug 2010) 2699–2701.
[15] A. Rogalski, Infrared detectors: status and trends, Prog. Quantum Electron. 27 (2003) 59–210.
[16] S.C. Lee, S. Krishna, S.R.J. Brueck, Quantum dot infrared photodetector enhanced by surface plasma wave excitation, Opt. Express 17 (2009) 23160–23168.
[17] J. Wang, J. Hu, P. Becla, A.M. Agarwal, L.C. Kimerling, Resonant-cavity-enhanced mid-infrared photodetector on a silicon platform, Opt. Express 18 (2010) 12890–12896.
[18] S. Kalchmair, R. Gansch, S.I. Ahn, A.M. Andrews, H. Detz, T. Zederbauer, E. Mujagi, P. Reininger, G. Lasser, W. Schrenk, G. Strasser, Detectivity enhancement in quantum well infrared photodetectors utilizing a photonic crystal slab resonator, Opt. Express 20 (2012) 5622–5628.
[19] W. Wu, A. Bonakdar, H. Mohseni, Plasmonic enhanced quantum well infrared photodetector with high detectivity, Appl. Phys. Lett. 96 (2010) 161107–161107-3.
[20] L. Lundqvist, J.Y. Andersson, Z.F. Paska, J. Borglind, D. Haga, Efficiency of grating coupled AlGaAs/GaAs quantum well infrared detectors, Appl. Phys. Lett. 63 (1993) 3361–3363.
[21] T.R. Schimert, S.L. Barnes, A.J. Brouns, F.C. Case, P. Mitra, L.T. Claiborne, Enhanced quantum well infrared photodetector with novel multiple quantum well grating structure, Appl. Phys. Lett. 68 (1996) 2846–2848.
[22] R.S. Attaluri, J. Shao, K.T. Posani, S.J. Lee, J.S. Brown, A. Stintz, S. Krishna, Resonant cavity enhanced InAs/In[sub 0.15]Ga[sub 0.85]As dots-in-a-well quantum dot infrared photodetector, J. Vac. Sci. Technol. B: Microelectron. Nanometer Struct. 25 (2007) 1186–1190.
[23] M. Zohar, M. Auslender, S. Hava, L. Faraone, Resonance cavity enhanced midinfrared photodetectors employing subwavelength grating, in numerical simulation of optoelectronic devices (NUSOD), in: 11th International Conference on, 2011, pp. 25–26.
[24] C.J. Hill, A. Soibel, D.Z.Y. Ting, S.A. Keo, J.M. Mumolo, J. Nguyen, M. Lee, S.D. Gunapala, High temperature operation of long-wavelength infrared superlattice detector with supressed dark current, Electron. Lett. 45 (2009) 1089–1090.
[25] B.F. Levine, C.G. Bethea, G. Hasnain, V.O. Shen, E. Pelve, R.R. Abbott, S.J. Hsieh, High sensitivity low dark current 10 μm GaAs quantum well infrared photodetectors, Appl. Phys. Lett. 56 (1990) 851–853.
[26] L.J. Kozlowski, G.M. Williams, G.J. Sullivan, C.W. Farley, R.J. Anderson, J. Chen, D.T. Cheung, W.E. Tennant, R.E. DeWames, LWIR 128×128 GaAs/AlGaAs multiple quantum well hybrid focal plane array, Electron Dev., IEEE Trans. 38 (1991) 1124–1130.
[27] F. Mohammedy, M. Jamal Deen, Growth and fabrication issues of GaSb-based detectors, J. Mater. Sci. Mater. Electron. 20 (2009) 1039–1058.
[28] Y.K. Su, J. Fuh-Shyang, C. Shing-Ming, C. Cheng-Der, C. Ya-Tung, 1/f noise and specific detectivity of HgCdTe photodiodes passivated with ZnS–CdS films, Quantum Electron., IEEE J. 35 (1999) 751–756.
[29] N. Fang, H. Lee, C. Sun, X. Zhang, Sub-diffraction-limited optical imaging with a silver superlens, Science 308 (2005) 534–537.
[30] D.K. Gramotnev, S.I. Bozhevolnyi, Plasmonics beyond the diffraction limit, Nat. Photon. 4 (Feb 2010) 83–91.
[31] J. Kohoutek, A. Bonakdar, R. Gelfand, D. Dey, I. Hassani Nia, V. Fathipour, O.G. Memis, H. Mohseni, Integrated all-optical infrared switchable plasmonic quantum cascade laser, Nano Lett. 12 (2012) 2537–2541.
[32] R. Quidant, Surface plasmon optics for enhanced light–matter interaction (2008) MMA4.
[33] C.-C. Chang, Y.D. Sharma, Y.-S. Kim, J.A. Bur, R.V. Shenoi, S. Krishna, D. Huang, S.-Y. Lin, A surface plasmon enhanced infrared photodetector Based on InAs quantum dots, Nano Lett. 10 (2010) 1704–1709.
[34] J.B. Khurgin, G. Sun, R.A. Soref, Enhancement of luminescence efficiency using surface plasmon polaritons: figures of merit, J. Opt. Soc. Am. B 24 (2007) 1968–1980.
[35] L. Novotny, N. van Hulst, Antennas for light, Nat. Photon. 5 (Feb 2011) 83–90.
[36] A. Archambault, T.V. Teperik, F. Marquier, J.J. Greffet, Surface plasmon Fourier optics, Phys. Rev. B 79 (2009) 195414.
[37] R. Yang, M.A. Abushagur, Z. Lu, Efficiently squeezing near infrared light into a 21 nm-by-24 nm nanospot, Opt. Express 16 (2008) 20142–20148.
[38] A. Yariv, in: Quantum Electronics, third ed., John Wiley, 1989.