An efficiency and response enhanced metamaterial single photon detector

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***Abstract*-With asymmetric split ring metamaterial periodically placed on top of the niobium nitride (NbN) nanowire meander, we theoretically propose a kind of metal-insulator-metallic (MIM) metamaterial nanocavity to enhance absorbing efficiency and shorten response time of the superconducting NbN nanowire single photon detector (SNSPD) operating at wavelength of 1550 nm. Up to 99.6% of the energy is absorbed and 96.5% dissipated in the nanowire. Meanwhile, taking advantage of this high efficiency absorbing cavity, we implement a more sparse arrangement of the NbN nanowire of the filling factor 0.2, which significantly lessens the nanowire and crucially boosts the response time to be only 40% of reset time in previous evenly spaced meander design. Together with trapped mode resonance, a standing wave oscillation mechanism is presented to explain the high efficiency and broad bandwidth properties. To further demonstrate the advantages of the nanocavity, a four-pixel SNSPD on 10 μm×10 μm area is designed to further reduce 75% reset time while maintaining 70% absorbing efficiency. Utilizing the asymmetric split ring metamaterial, we show a higher efficiency and more rapid response SNSPD configuration to contribute to the development of single photon detectors.**

I. Introduction

Since its first demonstration by Gol'tsman about a decade ago [1], superconducting nanowire single photon detector has emerged great potential applications in photon-counting classical optical communication [2], long-distance quantum key distribution [3,4], distributed fibre sensing [5], space-to-ground communications [6] and characterization of the photon statistics of light sources [7], due to its orders of magnitude faster recovery time and timing precision, which are key characteristic metrics in integrated quantum information processing systems components.

To achieve the best tradeoff between high SDE and rapid response, much effort has been paid to optimize the structure, such as using nano-antennae [8, 9], nanocavities [10, 11], dividing into many pixels [12, 13], introducing plasmonics [14], and embedding into photonic circuits [15]. However, it remains a slippery barrier in practical applications although the recent work indeed made much progress.

II. Model and simulation method

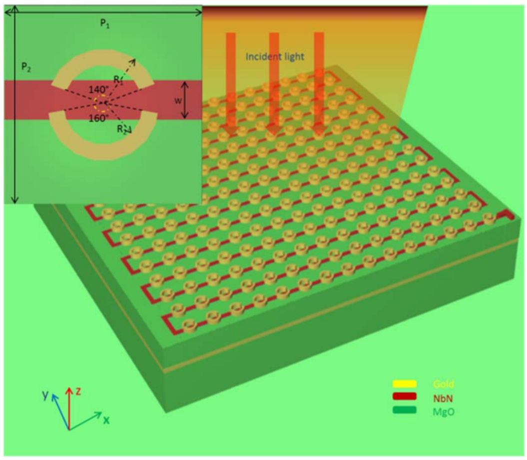
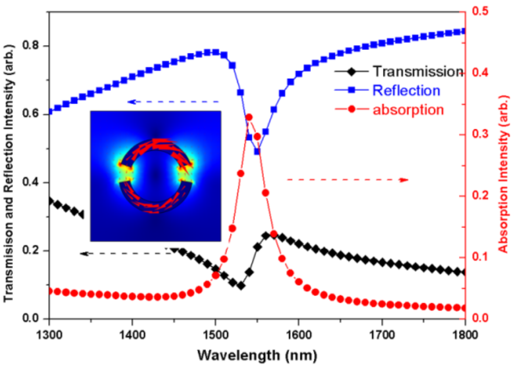


Fig.1. Schematic configuration of the metal-insulator-metallic asymmetric split ring metamaterial nanocavity. The magnesium oxide insulator layer between ASR and NbN nanowire is not depicted in this figure for the purpose of clearly showing nanowire details. The inset illustrates top view of one metamolecule and the structural denotations.

The nanocavity consisting of metal isolator asymmetric split ring metamaterial is shown in Figure 1. The cavity volume is filled with 500 nm magnesium oxide, sandwiched between 100 nm bottom gold film and asymmetric split rings, which are deposited on the substrate. The 120 nm wide nanowire is arranged in a meander configuration with a filling factor of 0.2 on top the magnesium oxide film. As shown, the nanowire is placed exactly below the ASR metamaterial with 5 nm thick and 120 nm wide magnesium oxide isolation layer (not shown in the figure) separating from each other.

III. Results and discussion

To demonstrate the advantages of the nanocavity mentioned above, we separately investigate the properties of asymmetric split rings metamaterials first. It has attracted much attention in microwave [16, 17, 18] and THz regime [19] because of its Fano resonance property [20, 21], which arises from the circular current distribution at resonant frequency, called trapped mode. Here we design the ASR metamaterial operating at wavelength of 1550 nm where the structures made of noble metals always suffer inevitable losses. Figure 2 shows the transmission, reflection and absorption spectra of asymmetric split ring metamaterial when illuminated by the incident light with



electric filed perpendicular to the symmetric axis of the ASR structure. We call this x-axis polarized excitation 'asymmetric axis polarization' since the electric field is along the asymmetric axis of the ASR. Elaborately tuning the structural parameters, the resonant wavelength of ASR metamaterial is shifted to 1550 nm.

FIG. 2. The transmission, reflection and absorption spectra of asymmetric split ring metamaterial. The inset shows the circular current (arrow) and electric field (colour) distributions at resonant wavelength of 1550 nm.

Acknowledgment

The authors acknowledge the support provided by the State Key Program for Basic Research of China (2013CB632705, 2011CB922004), the National Natural Science Foundation of China (10990104, 11334008, and 61290301), the Fund of Shanghai Science and Technology Foundation (16ZR1445300) and Shanghai Sailing Program (16YF1413200).

Reference

[1]G. N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams and R. Sobolewski, Appl. Phys. Lett. 79, 705 (2001).

[2]E. A. Dauler, B. S. Robinson, A. J. Kerman, V. Anant, R. J. Barron, and K. K. Berggren, D. O. Caplan, J. J. Carney, S. A. Hamilton, K. M. Rosfjord, M. L. Stevens, and J. K. Yang, Proc. SPIE 6372, 637212 (2006).

[3]H. Takesue, S. Nam, Q. Zhang, R. H. Hadfield, and Y. Yamamoto, Nat. Photon. 1, 343 (2007).

[4]R. H. Hadfield, J. L. Habif, J. Schlafer, R. E. Schwall, and S. Nam, Appl. Phys. Lett. 89, 241129 (2006).

[5]J. Hu, Q. Zhao, X. Zhang, L. Zhang, X. Zhao, L. Kang, P. Wu, and A. N. E. Power, J. Lightwave Technol. 30, 2583 (2012).

[6]M. E. Grein, A. J. Kerman, E. A. Dauler, O. Shatrovoy, R. J. Molnar, D.Rosenberg, J. Yoon, C. E. DeVoe, D. V. Murphy, B. S. Robinson, and D. M. Boroson, IEEE International Conference on Space Optical Systems and Applications 78–82 (2011).

[7]R. Kaspi, A. P. Ongstad, G. C. Dente, J. R. Chavez , M. L. Tilton, and D. M. Gianardi, Appl. Phys. Lett. 88, 041122 (2006).

[8]X. L. Hu, E. A. Dauler, R. J. Molnar, and K. K. Berggren, Opt. Expr. 19, 17 (2011).

[9]F. L. Chen, S. W. Wang, X. X. Liu, X. F. Wang, L. M. Yu, and W. Lu, Opt. Quant. Electron 45, 1179 (2013).

[10]K. M. Rosfjord, J. K. W. Yang, E. A. Dauler, A. J. Kerman, V. Anant, B. M. Voronov, G. N. Gol'tsman, and K. K. Berggren, Opt. Expr. 14, 527 (2006).

[11]M. Csete, A. Szalai, A. Sipos, and G. Szabó, Opt. Expr. 20, 17065 (2012).

[12]E. A. Dauler, A. J. Kerman, R. J. Molnar, V. Bolkhovsky, S. A. Hamilton, X. Hu and K. K. Berggren, "Detection efficiency superconducting nanowire single photon detectors," European Conference on Applied Superconductivity, (2009).

[13]E. A. Dauler, B. S. Robinson, A. J. Kerman, J. K. W. Yang, E. K. M. Rosfjord, V. Anant, B. Voronov, G. Gol'tsman and K. K. Berggren, IEEE Trans. Appl. Supercond. 17, 279 (2007).

[14]M. Csete, A. Sipos, A. Szalai, F. Najafi, G. Szabo, and K. K. Berggren, Sci. Rep. 3, 2406 (2013).

[15]W.H.P. Pernice, C. Schuck, O. Minaeva, M. Li, G.N. Goltsman, A.V. Sergienko, and H.X. Tang, Nat. Comm. 3, 1325 (2012).

[16]J. H. Shi, R. Liu, B. Na, Y.Q. Xu, Z. Zhu, Y.K. Wang, H.F. Ma, and T.J. Cui, Appl. Phys. Lett. 103, 071906 (2013).

[17]J. H. Shi, H. F. Ma, W. X. Jiang, and T. J. Cui, Phys. Rev. B 86, 035103 (2012).

[18]V. Savinov, A. Tsiatmas, A. R. Buckingham, V. A. Fedotov, P. A. J. de Groot and N. I. Zheludev, Sci. Rep. 2, 450 (2012).

[19]V. Savinov, V. A. Fedotov, S. M. Anlage, P. A. J. de Groot, and N.I. Zheludev Phys. Rev. Lett. 109, 243904 (2012).

[20]B. Luk'yanchuk, N. I. Zheludev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, and C. T. Chong, Nature Mater. 9, 707 (2010).

[21]V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev Phys. Rev. Lett. 99, 147401 (2007).