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Low Dimension Structures And Devices For New Generation Photonic Technology

D. H. Zhang^a, D.Y. Tang^a, T. P. Chen^a, T. Mei^b and X. C. Yuan^c

^a*School of Electrical and Electronic Engineering Nanyang Technological University, Singapore 679798*

^b*Institute of Optoelectronic Materials and Technology, South China Normal University, Guangzhou 510631, China*

^c*Institute of Modern Optics, Nankai University, Tianjin 300071, China*

Abstract. Low dimensional structures and devices are the key technological building blocks for new generation of electronic and photonic technology. Such structures and devices show novel properties and can be integrated into systems for wide applications in many areas, including medical, biological and military and advancement of science. In this invited talk, I will present the main results achieved in our competitive research program which aims to explore the application of the mesoscopic structures in light source, manipulation and imaging and integrate them into advanced systems. In the light source aspect, we have for the first time developed graphene mode-locked lasers which are in the process of commercialization. Nanocrystal Si embedded in dielectrics was formed by ion implantation and subsequent annealing. Si light emitting devices with external quantum efficiency of about 2.9×10^{-3} % for visible emission were demonstrated at room temperature and the color of emitted light can be tuned electrically from violet to white by varying the injected current. In light manipulation, loss compensation of surface plasmon polaritons (SPPs) using quantum well (QW) gain media was studied theoretically and demonstrated experimentally. The SPP propagation length was effectively elongated several times through electrical pumping. One and two microring resonators based on silicon on insulator and III-V semiconductors technologies have been successfully fabricated and they can be used as filter and switch in the photonic circuit. In imaging, both SPP and low dimension structures are investigated and resolution far beyond diffraction limit in visible range has been realized. The integration of the components in the three aspects into complicated systems is on the way.

Keywords: Mesoscopic structure, light source, manipulation, high resolution, imaging.

PACS: 78.67.Pt, 78.66.Sq, 42.30.-d, 42.72.Bj.

INTRODUCTION

Man-made micro- and nano-scale structured materials are capable of managing electrons or light in radically different ways, thereby providing new opportunities for the control and transfer of information [1-3]. From semiconductor quantum well structures to the currently hottest optical metamaterials, the conquest of nano-world has been occurring in almost every field of research [1-12]. Recent advances in nano-scale precision fabrication tools combined with more sophisticated electromagnetic modeling capabilities have stimulated the deeper awareness of the potential use of meso-scale structures. Using an artificial mesoscopic structure one can likely generate new light sources, manipulate light and design new components not previously realized such as a "perfect lens", permitting arbitrarily high resolution for writing, reading or imaging. In information technology, this will

improve the density of data storage enormously. Breakthroughs in biotechnology may also take place such that it brings a chance for human beings to see virus optically. In this article, we present some results of our investigation on the physics, design, and fabrication of artificial mesoscopic structures and applications in light source, light manipulation and high resolution imaging and sensing.

EXPERIMENT, RESULTS & DISCUSSION

Light source

Si light emitting devices (LEDs) with white-color emission and colors electrically tunable based on Si nanocrystals embedded in Si_3N_4 thin films have been demonstrated [13]. The Si LED is fabricated on 6" Si wafer with a process fully compatible with the main-stream CMOS process that is used in the fabrication of computer chips. Visible electroluminescence (EL) with colors electrically tunable from violet to white has been observed from the Si LED, as shown in Figure 1. The color tunability is realized by varying the full width at half maximum and the intensity of the two composite bands of the EL, i.e., the violet band and the green-yellow band with injection current. A strong white EL can be achieved with a relatively high injection current ($> \sim 200 \text{ mA/cm}^2$), demonstrating the realization of white-light Si LED.

The color tunability and the broadband of the Si LED are useful to the on-chip data communication as they can provide more controllable data channels. In addition, the white-light Si LED can be also used for biosensing applications, and microdisplay applications.

FIGURE 1. Si LED structure and light emission under different injection currents.

In collaboration with the researchers in National University of Singapore, we have for the first time proposed and successfully demonstrated the technology of using atomic layer graphene as saturable absorber to mode locking lasers [14]. Based on extensive systematic experimental studies, our team has shown that graphene as a saturable absorber to mode lock lasers possesses a variety of unique advantages compared with conventional technologies, such as easy to fabrication, super broad band saturable absorption, ultrafast recovery time etc. Fig. 2 shows the experimental setup and mode-locked pulse train. Our results have attracted worldwide attention of the material and laser research communities. The Magazine

NPG Asia Materials and Nanowerk have feature reported the result. Many other magazines or web sites, like I-Micronews, Nanotechnology for Development, Graphene-Info, have highlighted their result.

FIGURE 2. Experimental setup and the mode-locked pulse train with grapheme as the saturable absorber.

We have first demonstrated in the world a kind of dark pulse emission fiber laser. The features of the dark pulses generated in their laser resemble those of the light pulses generated in a conventional mode locked laser, but instead of being a train of light intensity pulses emitted by laser, a train of light intensity dips on top of a strong CW light beam is emitted by their laser. This is a completely new feature of laser operation not discovered before. The oscilloscope trace of a dark pulse emission of a fiber laser is shown in Fig. 3. The results attracted great attention by the laser research community. The prestigious international journal *Nature Photonics* has highlighted the result. The international magazine *Optics and Photonics focus* has written a feature article to report the work. Recently, we have further realized simultaneous emission of black-white pulses in a fiber laser, pushing a step further of people's understanding on the lasers, as shown in Fig. 4.

FIGURE 3. Oscilloscope trace of a dark pulse emission fiber laser. Vertical axis: Intensity (arb. unit.) Horizontal axis: time (1 μs/div.)

FIGURE 4. Oscilloscope trace of a simultaneously dark-bright pulse emission fiber laser first achieved by the team. Vertical axis: Intensity (arb. unit.) Horizontal axis: time (100ns/div.)

Light manipulation

With the mesoscopic structures, we demonstrated gain compensated surface Plasmon (SP) propagation using electrically pumped semiconductor media [15]. Intrinsically, SP propagation is lossy due to metal absorption, whereas the active control of SPs, including generation, amplification and modulation, becomes vital to the success of plasmonics. So far people have demonstrated SP lasing via both electrical and optical pumping, but there is no experimental result of SP amplification. Gain assisted elongation of SP propagation is on the way towards SP amplification, while all had been demonstrated via optical pumping. In our work, we adopted the quantum-well semiconductor as the active media to provide gain for SP propagation along the gold waveguide shown in Fig. 5. It is found that the propagation length of the short range SP increases drastically as the gain goes up. Experimentally we have achieved an increase of 3.5 times of the output via electrical pumping as shown in Fig. 6), which gives a key step toward SP amplification. To the best of our knowledge, this is the first demonstration of gain-assisted propagation by electrical pumping.

FIGURE 5. The schematic of the device for active SP control

FIGURE 6. The output of the SP waveguide at electrical bias.

We developed box-like optical filter based on two-dimensional arrays of resonator. The conventional box-like filter is based on one dimensional array of microring resonators and usually suffers from the limitation of either high sidelobes (low extinction ratio) or high ripples (non-flat filter band). This problem can be overcome in two-dimensional array of microring resonators. Our device was fabricated in silicon-on-insulator (SOI) technology, with ring radius of $5\mu\text{m}$ and waveguide width of 450nm . The results shows sidelobe suppression of 13dB and a band ripple of less than 0.2dB . The bandwidth for (3×4) and (3×8) arrays are 500GHz and 750GHz , respectively. This can be useful for microwave photonics application. The shape-factor is measured to be 0.7 (for 3×4) and 0.8 (for 3×8). The optical filter we developed has high performance and much lower cost. The structure (a) and performance (b) of two dimensional arrays box-like filter (i.e., 3×8 arrays), compared to the one dimensional one (1×8) are shown in Fig. 7.

FIGURE 7. The structure (a) and performance (b) of two dimensional arrays box-like filter (i.e., 3×8 arrays), compared to the one dimensional one (1×8).

High resolution imaging

We proposed a new beam splitter consisting of a silver-alumina composite metamaterial coated by a layer of chromium containing one slit. The simulation results show that beam splitting occurs when the width of the slit is much shorter than the incident wavelength. By adding another slit, the metamaterial structure can also show the deep sub-wavelength resolution capability in the far field when the silver layer under the slits is thicker than a critical value. It is believed that such structures have potential applications in nanophotonics devices and superresolution imaging. Fig. 8 shows the beam splitting in designed two-slit structures.

A hemispherical hyperlens for two dimensional imaging has been designed and a resolution less than 100 nm is numerically demonstrated. The hyperlens consists of several layers of concentric Ag- Al_2O_3 hemispherical shells embedded in a quartz substrate. The geometry of the hemispherical hyperlens is illustrated in Fig. 9. The top layer of the substrate is covered by Chromium (Cr). The image will be projected along the radial direction and the final image will be located at the backside of the quartz substrate. Since the imaging area is in hemispherical shape, the image projected to the image plane provides 2-dimensional information of the object. By further processing of the image projected to the image plane, a 3-dimensional image can be reconstructed.

FIGURE 8. Energy flows in the structures designed.

FIGURE 9. Hyperlens structure, object (a) and image (b).

We are the first to demonstrate a novel optical microscopy method and system that can achieve non-invasive and wide-field high-resolution images in real-time by utilizing the standing surface plasmon polaritons (SPPs) excited by localized fields originating from optical vortices (OV) [16]. Optical configuration of the OV-induced standing wave surface plasmon resonance fluorescence (SW-SPRF) microscopy is shown in Fig. 10 (a). When an OV emanating from the objective lens and converging towards the geometric focus, it gives rise to a diffraction-limited spot containing a large spectrum of wavevectors limited by the numerical aperture (NA) of the lens. Therefore, by selecting two sets of diametrically opposed waves with SPR angles of $\pm\theta_{sp}$, two counter propagating SPP waves with wavevector of $\pm k_{sp}$ will be generated. The SPP waves will propagate towards the OV beam center to form a localized SW field if the SPP propagation length is longer than the radius of OV. Due to such an excitation scheme, SPPs are highly confined near the interface and intrinsically localized in a small volume, resulting in spatially localized to dimensions smaller than the wavelength with high-spatial-frequency information, thereby improving the imaging resolution. These waves will subsequently excite fluorescent beads on the metal plate.

FIGURE 10. (a) Optical configuration of SPPs generated by OV which are focused onto the Ag thin film. The interference pattern, which is generated by two counter propagating SPPs under resonant condition, is used to excite the fluorescent beads deposited in the dark core of OV beam and (b) Schematic diagram of experimental setup.

Figure 10(b) shows a schematic diagram of our experimental setup. We excite SPPs on Ag layer with a highly focused, linearly polarized OV beam. The OV beam is generated by collimated laser beam coming from a helium-neon laser at the wavelength of 633 nm. The parallel-aligned nematic liquid crystal spatial light modulator (SLM) is used to imprint computer-generated patterns of phase shifts onto the wavefront of the incident beam. The modulated wavefront is then transferred by a telescope to the back aperture of an oil immersion objective lens

with a NA of 1.45, corresponding an angle spread of $2 \times 73^\circ$, well beyond the range for SPR angular modulation. In our experiment, we deposit the fluorescent polystyrene microspheres (diameter 20 nm, peak emission at 645 nm, Molecular Probes) on a silver substrate. The fluorescence emission is collected by the same objective lens and the emitted light images are relayed to the charge-coupled device (CCD) camera through the dichroic mirror along the emission path.

FIGURE 11. (a1) Original SPRF image with doughnut-shape PSF, (b1) deconvolved SPRF image with SPCE PSF kernel, (c1) SW-SPRF image after applying SW-TIRF algorithm and linear Richardson-Lucy linear deconvolution. (a2)-(c2) Comparison of PSF profiles at a selected region of interest in (a1)-(c1).

We observe the doughnut shape images in Fig. 11(a1) when the fluorescent excitation light is coupled back via the Ag film to the CCD. Therefore, the deconvolution algorithm is applied to convert the original doughnut-shape point spread functions (PSFs) into PSFs that are single lobed as shown in Fig. 11(b1) by using the surface-plasmon-coupled emission (SPCE) PSF kernel. Subsequently followed by the application of the SW-TIRF algorithm, the SW-SPRF resolution enhanced image is shown in Fig. 11(c1). The PSF profile in Fig. 11(c2) demonstrates that the full width half maximum (FWHM) of SW-SPRF is more than a factor of 2 narrower than that of the deconvolved SPRF PSF in Fig. 11(b2). The numerical studies and experimental results reveal an achievement of 0.25λ (~ 150 nm by using 632 nm light source) optical resolution, a factor of twofold improvement compared with the standard total-internal-reflection fluorescence (TIRF) microscopy. Additionally, the imaging system provides higher enhancement on the transmission intensity and the detected signal may contain more information from farther regions than the other microscopy such as TIRF microscopy.

CONCLUSION

In conclusion, we have studied mesoscopic structures and their applications in light source, manipulation and imaging. These include first application of graphene for mode-locked lasers, nanocrystal Si LEDs with color electrically tunable from

violet to white by varying the injected current, demonstration of loss compensation of surface plasmon polaritons (SPPs) using quantum well (QW) gain media, microring resonators based on silicon on insulator and III-V semiconductors technologies for filter and switch in the photonic circuit, and metamaterial hyperlens and standing wave surface plasmon resonance fluorescence (SW-SPRF) microscopy with resolution beyond diffraction limit. The integration of the components in the three aspects into complicated systems is on the way.

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