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Coherent light squeezing states within a modified microring system

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ABSTRACT

We have proposed the simple method of the squeezed light generation in the modified microring resonator, which is known as the microring conjugate mirror (MCM). When the monochromatic light is input into the MCM, the general form of the squeezed coherent states for a quantum harmonic oscillator can be generated by controlling the additional two side rings, which are the phase modulators. By using the graphical method called the Optiwave program, the coherent squeezed states of coherent light within an MCM can be obtained and interpreted as the amplitude, phase, quadrature and photon number-squeezed states. This method has shown potentials for microring related device design, which can be used before practical applications.

The concept behind squeezing of light includes the fact that the presence of photons (light particles) causes electromagnetic fluctuations in that region, which is called as 'noise'. The noise gets larger with the intensity of the light. However, the situation changes at a very fine quantum level, where the noise still exists when there is no light. This is called as vacuum noise. It may seem that there is nothing (no photon) but there is always a little bit more than nothing. At such a fine quantum level, things get really strange. The noise level can further be lowered, lower than the vacuum noise. This is what physicist term as squeezing of light. The squeezing of light is a strange quantum physics phenomenon, it produces a specific type of light called low noise. An approach for squeezing of light is by exciting a single atom by a very small amount of light which is called resonance fluorescence. Its mathematical basis came out nearly four decades ago [1–5]. The low noise produced by squeezing of light is extremely difficult to measure experimentally [1]. A team of physicists at Cambridge University has recently demonstrated the squeezing of light using semiconductor quantum-dot. This noise is introduced by the light (photon) travelling in the system with the oscillation angular frequency, ω. Generally, the squeezed photons can be generated within the optical system whenever the uncertainty value ($\Delta x.\Delta p$) is saturated, which is formed by the nonlinear effect known as a four-wave mixing (FWM) [6]. Theoretically, the quantum noise is introduced by the squeezed photons and has affected the optical system performance. Therefore, all optical systems are required to operate over the quantum noises, which has become the required optical system specification. Nevertheless, this is the system's limitation that must be amended to fulfil the desired application's requirements. Practically, when a light pulse from a monochromatic source in either a common (Gaussian pulse) or fiber laser (soliton pulse) is input into the micro-ring resonator (waveguide) system, such a light pulse behavior can be described and interpreted by using the well-established mathematical model [7,8]. The dynamic of a pulse within the device and output of light via each port can be found and the different interpretations obtained. Firstly, the transfer function of the output can be obtained by using the ray tracing method called Mason's rule [9]. Secondly, the wave propagation within the device and the output light can be described by using the wave equation, where the outputs in terms of transverse electric and magnetic fields can be obtained. Moreover, the leaky mode of the waves within the ring system can also be observed, from which the optimum leaky mode

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known as the whispering gallery mode (WGM) can also be obtained by controlling the specific conditions [10–12].

We understand that mathematical complexity is not necessary to obtain simulation results. By using graphical approach, the required parameters can be acquired and used in the existing equations. Simple mathematical formulae can be used to obtain required results. In this work, the squeezing of the photon is the required of the system shown in Fig. 1. The acquired parameters are then be used to perform the mathematical simulations. The optical field (E) propagates through the z-axis within a microring system as shown in Fig. 1(a) is given by $\boldsymbol{E_z = E_{i1} = E_0 e^{-ik_z t - \omega t}}$ [13]. Where E_0 is the electric field amplitude (real), $\boldsymbol{k_z}$ is the wave number in the direction of propagation and $\boldsymbol{\omega}$ is the angular frequency. The sinusoidal electric field E(t) can be expressed as a sum of two complex time-variable quantities a(t), and $\dot{a}$ (t), $E(t) = \frac{1}{2}$ [a(t) + $\dot{a}$ (t)]. These quantities are phase modulators that rotate in the complex plane with time, which can be described in terms of a complex amplitude a and $\dot{a}$ time-dependent factor $e^{i\omega t}$. The complex amplitude is given as a = x + ip, where $\boldsymbol{x}$ and p are real. By inverting these relationships, the quadrature components $\boldsymbol{x}$ and p are expressible in terms of a and $a*$ so that the electric field can be expressed as E(t) = xcos ωt + psinωt, x = (a + $\dot{a}$)/2, p = (a – $\dot{a}$)/(2i). The squeezed coherent states by the "Heisenberg Uncertainty Principle" $\Delta x\Delta p = /2$, with reduced uncertainty in one of its quadrature components and increased uncertainty in the other. As indicated in Fig. 1, the quantum harmonic oscillator of angular frequency, ω, can be disturbed by the two side ring photons to create photon distribution, that will be randomly coupled from the simultaneous creation and annihilation operations carried through the induced FWM behavior. The interesting effect of four-wave mixing technique provides a way to estimate the uncertainty value when it reaches a saturation [5], which can lead to the observed squeezed states, from which the photons will be squeezed from the ring resonator system. The squeezed state of photons in the vacuum state is obtained by the photon oscillation in the ground state, where the squeezed photon state position is observed by oscillation along the displacement (x). Generally, there are the other states of squeezed photon states called the excited squeezed states by the FWM effects introduced by the creation and annihilation enforcements, which will introduce the changes in frequency oscillations (energy of state), which is as shown in the below details. The magnitude of the complex term is the unity, which is not affected to the system, finally, the relation $\Delta x\Delta p = /2$is obtained, from which $\Delta x$is approximated to be $[(/(2m\omega))]^2$. In this article, the use of the modified microring resonator is configured as the microring conjugate mirror is proposed and manipulated by controlling the phase modulators. By using the graphical method called the Optiwave program, the squeezed coherent light within the system can be generated and controlled. The theoretical background is given and the numerical formulae provided.

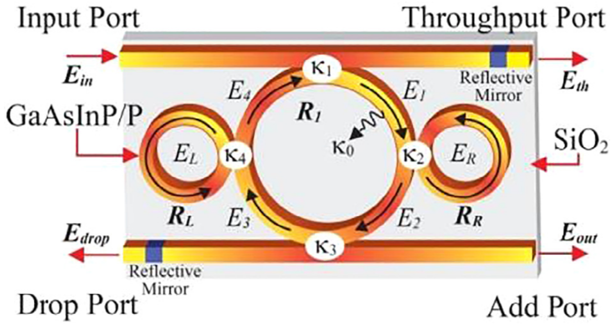

Fig. 1. A schematic of the microring conjugate mirror, where E_{in}, E_{th}, E_{drop}, E_{add} and E_s are the optical field of the input, throughput (or through), drop, add ports and propagation fileds respectively, R_L: Reft hand ring radius, R_R: Right hand ring radius,: Center ring radius, κ_s: coupling constants, which is 0.5 for all κs.

A micro-conjugate mirror is designed and formed by a nonlinear micro-ring resonator. It is a modified optical add-drop filter as shown in Fig. 1. Such a device can be used to form the 3D imaging pixel [12]. It is initially used to generate the whispering gallery modes (WGM) of light [10]. The optical field (E_1) is input into the system, from which the propagation and output fields of all ports of the system are given by the following forms in the given Eqs. (1)–(9) [12].

$$E_1 = \sqrt{1-\gamma_1}\left(\sqrt{1-\kappa_1}E_4 e^{-\frac{\alpha L_D}{2\,2}-jk_n\frac{L_D}{2}} + j\sqrt{\kappa_1}E_{i1}e^{-\frac{\alpha L_D}{2\,4}-jk_n\frac{L_D}{4}}\right) \tag{1}$$

$$E_{R2} = E_{R1}e^{-\frac{\alpha}{2}L_R - jk_nL_R} \tag{2}$$

$$E_2 = \sqrt{1-\gamma_2}(\sqrt{1-\kappa_2}E_1 + j\sqrt{\kappa_2}E_{R2}) \tag{3}$$

$$E_3 = \sqrt{1-\gamma_3}(\sqrt{1-\kappa_3}E_2 e^{-\frac{\alpha L_D}{2\,2}-jk_n\frac{L_D}{2}} + j\sqrt{\kappa_3}E_{i2}e^{-\frac{\alpha L_D}{2\,4}-jk_n\frac{L_D}{4}}) \tag{4}$$

$$E_{L2} = E_{L1}e^{-\frac{\alpha}{2}L_L - jk_nL_L} \tag{5}$$

$$E_4 = \sqrt{1-\gamma_4}(\sqrt{1-\kappa_4}E_3 + j\sqrt{\kappa_4}E_{L2}) \tag{6}$$

$$E_d = \sqrt{1-\gamma_3}(\sqrt{1-\kappa_3}E_{i2} + j\sqrt{\kappa_3}E_2 e^{-\frac{\alpha L_D}{2\,4}-jk_n\frac{L_D}{4}}) \tag{7}$$

$$E_{th} = \sqrt{1-\gamma_1}(\sqrt{1-\kappa_1}E_{i1} + j\sqrt{\kappa_1}E_4 e^{-\frac{\alpha L_D}{2\,4}-jk_n\frac{L_D}{4}}) \tag{8}$$

$$E_{out} = \sqrt{1-\gamma_3}(\sqrt{1-\kappa_3}E_d + j\sqrt{\kappa_3}E_2 e^{-\frac{\alpha L_D}{2\,4}-jk_n\frac{L_D}{4}}) \tag{9}$$

Where $E_d^* = -nE_d$, where the complex conjugate electrical field is the phase term is involved and presented the microring conjugate mirror, κ is the coupling factor, γ is the intensity insertion loss coefficient of the directional coupler, α is the intensity attenuation coefficient of the ring, where $kn = 2\pi \cdot n_{eff}$, n_{eff} = the effective refractive index. n is the reflection ratio. L_D = the circumference of the center ring, L_R is the circumference of the right ring, L_L is the circumference of the left ring.

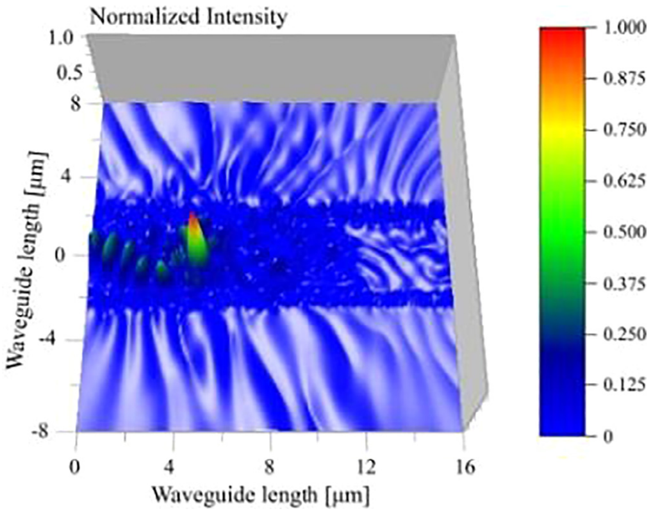

Fig. 2. Amplitude squeezing state: where $R_L = R_R$ = 0.88 μm, R_1 = 1.55 μm, the input monochromatic light source wavelength(??) is 1.55 μm, the peak power is at 5.0 mW, the material is GaAsIn/InP. The refractive index of the silicon is 1.46. The linear and nonlinear refractive indices of the GaAsInP/P are 3.14 and 1.30 × 10^{-13} m^2 W^{-1}, respectively. The attenuation coefficient of the waveguide is 0.1 dB (mm)$^{-1}$.

The squeezed photons within a modified microring resonator are modelled and manipulated. The requirement of the squeezed monochromatic light is the propagation media has to be the nonlinear medium. The microring resonator is made of the GaAsInP/P, which is a nonlinear material. The two side rings are added to increase in terms of phase changes. Moreover, the reflected ends of the through and drop ports are introduced to form the stronger coupling power of the microring conjugate mirror. The description of the different types of squeezed coherent light is found in the references [2–4,13,14]. Here, the graphical method is used to manipulate the squeezed light generation, where the changes in light phases of the coherent light propagating within the system are introduced by the two nonlinear side rings. However, the electrical fields within the system can also be found by the mathematical formulae of Eqs. (1)–(9). The proposed device parameters are the practical device parameters that can be fabricated by the current technology [15]. The four types of squeezed light can be manipulated and occurred, where they are (1) the amplitude squeezed state has occurred when the phase difference between two side ring is equal to zero, $R_L = R_R$, (2) the phase squeezed state is obtained when the squeezed pulse is occurred within the center of the rings, while the different ring radii of the two ring resonators are the phase modulator, is suitable, the quadrature squeezed state occurs when the squeezed light occurs between the center rings and the circumferences, where the suitable ring radii of the phase modulators are applied, and (4) photon-number squeezed state occurs on the ring circumferences.

The mathematical formulae of the squeezed light generation within the MCM are provided by the Eqs. (1)–(9), which are used to described the propagation of light within the MCM. However, this is the graphical method using the Optiwave program [10] to find the squeezed state, where the variation of the two side rings are performed to manipulate of the all possible cases of the squeezed photons within the MCM presented. The results of the amplitude squeezing state are shown in Fig. 2. Fig. 3 shows the phase (coherent) squeezed states, while the quadrature and photon number-squeezed states are shown in Figs. 4 and 5, respectively. The used parameter is provided by the related figure captions.

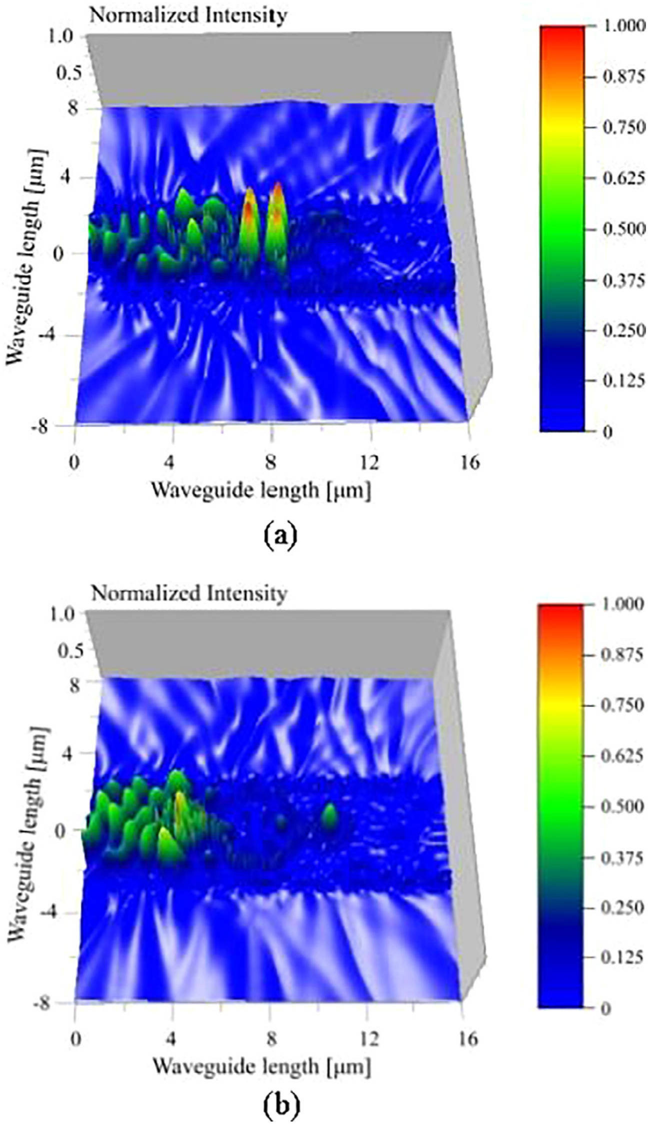

Fig. 3. Phase squeezing state, where (a) R_L = 0.86 μm, R_R: 0.87 μm, R_1 = 1.40 μm, (b) R_L = 0.87 μm, R_R: 0.88 μm, R_1 = 1.80 μm. The coupling effect is introduced to the two side rings by the center ring, while the coupling effect is introduced to the centering by the phase modulators.

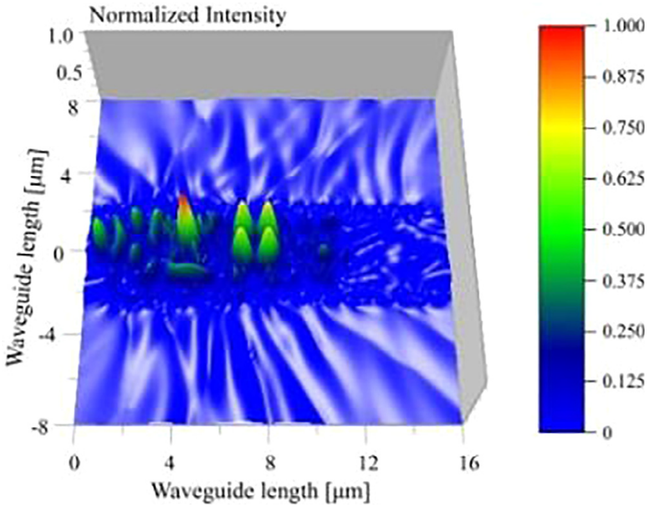

Fig. 4. Quadrature squeezing state, where R_L = 0.87 μm, R_R: 0.86 μm, R_1 = 1.55 μm.

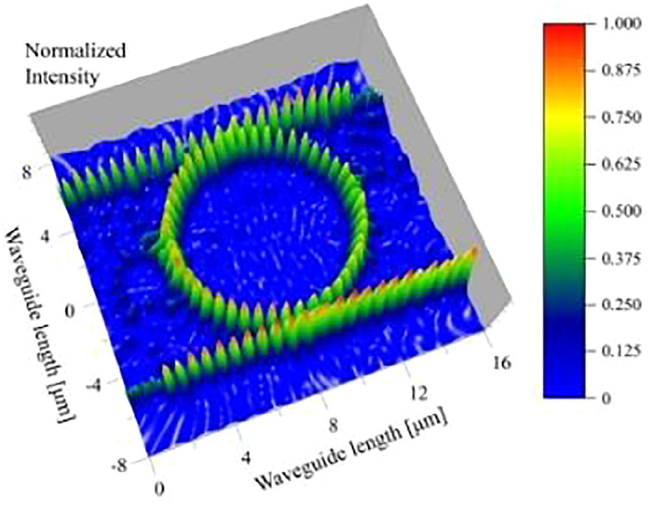

Fig. 5. Photon number squeezing state: where $R_L = R_R$ = 1.1 μm, R_1 = 4.0 μm, TiO_2 length is 10 nm.

The simple technique of finding the coherent light squeezing in an MCM was presented. The results obtained have shown that the proposed method is a very interesting mean for squeezing the light within a microring resonator configured as the quantum harmonic oscillator. By controlling the side ring phase modulators, the squeezed light states are obtained. Squeezed light at nanoscale dimensions using standard dielectric waveguide coupled to plasmonic waveguide brings possible applications in high-speed optical signal processing, nanostructure manipulation, overcoming shot-noise and diffraction limits in biological-microscopy imaging, photonic- force microscopy. The use for microring related device design, for instance, light source, quantum information source, photon switching control, quantum memory, where the required squeezing outputs can be controlled for suitable applications [16–19].

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rinp.2018.02.041.

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