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Efficient Generation of Squeezed Light Based on MgO-Doped Periodically Poled LiNbO$_3$ *

KONG De-Huan(孔德欢), LI Zong-Yang(李宗阳), WANG Xu-Yang(王旭阳), LI Yong-Min(李永民)**
State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006

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We demonstrate a high-efficiency green light conversion from an external cavity second harmonic generation with a MgO-doped periodically poled LiNbO$_3$ crystal. The frequency doubler can reach a conversion efficiency of 64% with a fundamental power of 26 mW. Meanwhile, the generated green light is quadrature-amplitude squeezed and 1.2 dB green light squeezing is experimentally measured. The squeezing at different pump levels is also investigated and is in good agreement with the theoretical prediction.

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Squeezed lights can improve precision measurements below the standard quantum noise limit for optical detection. They are also key resources for quantum information processing, such as quantum teleportation and quantum cryptography. The application of quasi-phase matching nonlinear crystals has made the generation of non-classical quantum states of light more efficient and practical with the ability to engineer nonlinear materials for the desired interactions. The periodically poled LiNbO$_3$ (PPLN) crystal has been used in the generation of squeezed light field and entangled photons[1−6] due to its large optical nonlinearity ($d_{\rm eff} = (2/\pi)d_{33} = 16\,{\rm pm/V}$) compared with other periodically poled materials, such as periodically poled KTiOPO$_4$ (PPKTP) and periodically poled LiTaO$_3$. MgO doped PPLN (MgO:PPLN) crystal is preferred to PPLN for better resistance to photo-refractive damage. The combination of its near room-temperature operation and high nonlinearity make it an attractive nonlinear material for many applications. Various applications in nonlinear optical frequency conversion have been demonstrated.[7−10] Recently, Masada *et al.* reported the generation of 860 nm squeezed light utilizing a sub-threshold optical parametric oscillator with a MgO:PPLN crystal.[11] Crisafulli *et al.* demonstrated the shaping of squeezed light in an optical parametric oscillator network with MgO:PPLN crystals.[12]

Both PPKTP and PPLN have been utilized to prepare the amplitude-squeezed light by second harmonic generation (SHG).[2,13,14] However, there are few reports on the generation of non-classical states with the MgO:PPLN.[11,12] To our knowledge, there has been no report of squeezed light generation through MgO:PPLN based frequency doubling. In this Letter, we report a high-efficiency green light conversion and preparation of quadrature-amplitude squeezed green light from an external cavity SHG with a bulk MgO:PPLN crystal. With a fundamental power of only 26 mW, the frequency doubler can attain a conversion efficiency of 64% and 1.2 dB green light squeezing was experimentally observed. The squeezing at different pump levels has also been investigated and is in good agreement with the theoretical prediction.

The experimental setup is depicted in Fig. 1. The pump laser is a single frequency Nd:YVO$_4$ laser, which delivers 1000 mW of infra-red power at 1064 nm. A 40-dB faraday isolator effectively eliminates undesired back-reflection laser. The combination of a half waveplate and a polarizing beamsplitter is used to adjust the input power of the frequency doubler. The laser is carefully mode matched (with efficiency of 95%) to a narrow line-width ring cavity (mode cleaner), which is used to improve the transverse-mode and to reduce the excess amplitude and phase noises of the laser field. The intensity noise of the transmitted laser can reach the shot noise limit (SNL) at frequencies above 6 MHz when the mode cleaner cavity length was actively locked to the laser frequency. Then, the pump beam is focused onto the center of the SHG cavity by two plano-convex lenses with a sptial-mode matching efficiency of 93%. The SHG cavity consists of an input coupler with a transmission of 1.85% at 1064 nm and high reflectivity at 532 nm ($R > 99.8\%$), an output coupler that is highly reflective at 1064 nm ($R > 99.8\%$) and high transmission at 532 nm ($T = 98.5\%$). The radius of the two curved mirrors is 20 mm and the total cavity length is 42 mm, which results in a Boyd–Kleinmann focusing factor of 0.2. The MgO:PPLN crystal with 5 mol% MgO doping (HC Photonics) has dimensions of 1 mm × 2 mm × 10 mm (thickness × width × length)

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**Corresponding author. Email: yongmin@sxu.edu.cn and 6.94 µm grating period. Both of the crystal's end faces have an antireflection coating at 1064 nm and 532 nm. By measuring the finesse of the cavity, the intracavity loss is determined to be 0.5%.

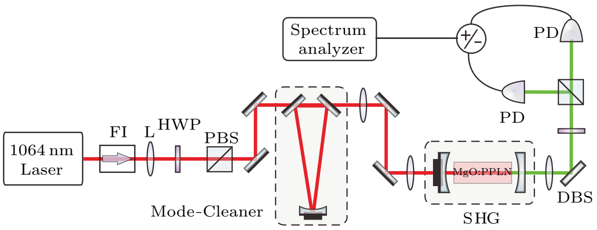

Fig. 1. (Color online) Schematic diagram of the experimental setup. FI: faraday isolator; L: lens; HWP: half waveplate; PBS: polarizing beam splitter; DBS: dichroic beam splitter; PD: photodetector.

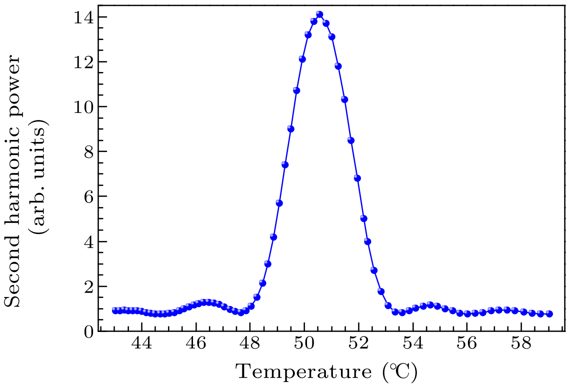

Fig. 2. (Color online) Temperature tuning curve for second harmonic generation in MgO:PPLN.

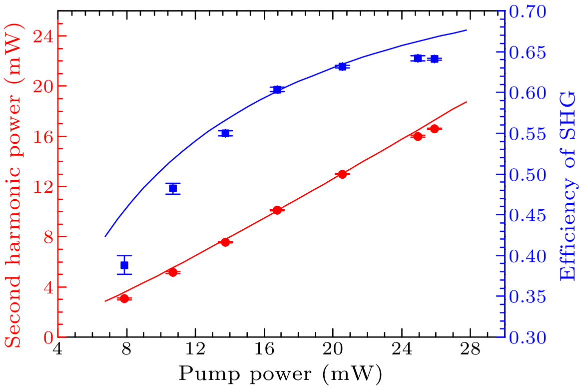

Fig. 3. (Color online) The second harmonic (SH) power and frequency doubling efficiency versus the fundamental power. Solid squares: efficiency of SHG; solid circles: SH power. The solid lines are theoretical fit.

To find the optimal phase matching temperature, we measured the frequency doubling efficiency of the MgO:PPLN crystal as a function of its temperature. Figure 2 shows the measured result, and it is clear that the optimal phase matching temperature is 50.5℃ and the temperature range for the phase matching (full width, half maximum) is 2.65℃. In our experiment the crystal was put inside a temperature-controlled copper oven that is enclosed with polysulfone to ensure a stable and accurate phase matching temperature.

The SHG cavity was stabilized by an electric servo to ensure that the cavity frequency coincides with the pump laser frequency. The output 532 nm light was separated from the 1064 nm light by a dichroic beamsplitter. Figure 3 shows the emitted green light power and the corresponding conversion efficiency as a function of the fundamental power. When the pump power increases to 26 mW, the green light of 16.6 mW was generated and the frequency doubling efficiency is 64%. Theoretical fit was also shown by using the experimental parameters (the only free parameter is the nonlinear conversion factor $\gamma_{\rm SHG} = 0.0078\,{\rm W}^{-1}$).[2]

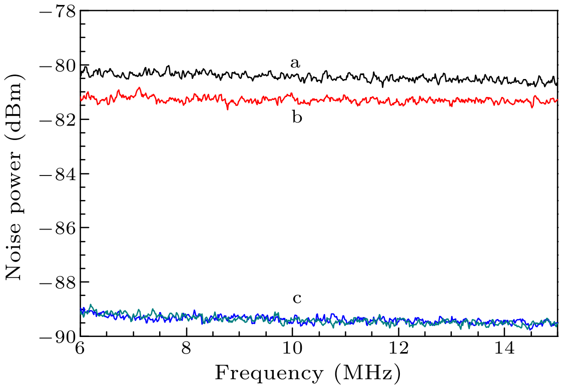

Fig. 4. (Color online) The quadrature amplitude squeezing spectrum of the 532 nm field. (a) SNL; (b) quadrature amplitude squeezing spectrum; (c) electronic dark noise.

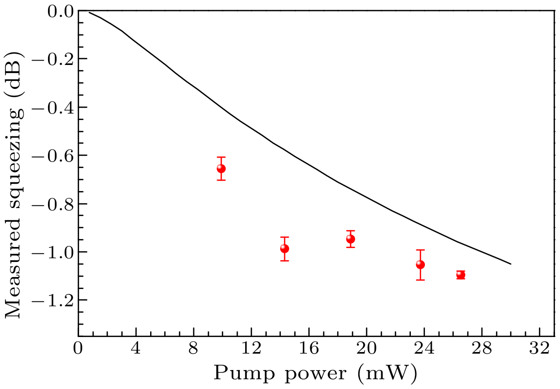

Fig. 5. (Color online) The amplitude squeezing of 532 nm optical field versus the fundamental power. Solid circles: experimental results; solid line: theoretical fitting; analysis frequency: 8 MHz.

To investigate the quadrature amplitude noise of the green light, the beam was sent to a 50/50 beam splitter, which consists of a half waveplate and a polarizing beamsplitter. The resultant beams were directed to two balanced detectors, which were built from two S5973 photodiodes (Hamamatsu) with a measured quantum efficiency of 85% at 532 nm. The currents of the two balanced detectors were either added (the quadrature amplitude noise) or subtracted (SNL), which were further recorded by using a spectrum analyzer. Figure 4 shows the typical squeezed spectrum of the green light at frequencies from 6 MHz to 15 MHz, the electronic dark noises of the detection system when no light is incident are also shown (Fig. 4(c)). The fundamental and SH power are 26 mW and 16.6 mW, respectively. Because the laser exhibits excess amplitude noise at low frequency range and the finite linewidth of the mode cleaner, the green light is only amplitude squeezed at frequencies above 4.5 MHz. The maximum squeezing of 0.94 dB was directly observed at 8 MHz. When we consider the detection efficiency of 81%, the inferred amount of squeezing is 1.2 dB.

We also investigate the green light amplitude squeezing performance of the MgO:PPLN based external cavity SHG system at different fundamental powers. The observed squeezing as a function of the fundamental power is shown in Fig. 5. The solid circles are the experimental values and the solid line is the theoretical fit.[2] The analysis frequency is fixed at 8 MHz and the electronic dark noise has been subtracted. We can see that the squeezing increases with the increasing pump power and there is a qualitative match between the theory and experiment.

In conclusion, based on a MgO:PPLN crystal, high-efficiency green light conversion from an external cavity frequency doubler with conversion efficiency of 64% has been achieved. At a low pump power of only 26 mW, quadrature-amplitude squeezing of 1.2 dB is successfully observed. Our results show that MgO:PPLN is a good candidate for generating short-wavelength squeezed light field based on the SH process. Higher SHG efficiency and larger squeezing should be made possible by optimizing the relevant optical setup, including better coatings of the cavity mirrors and the nonlinear crystal, to reduce unwanted intracavity losses. Also, better stability of the mode cleaner and SHG cavity is crucial to a high degree of squeezing.

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