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Letter

1-μm laser with natural phase matching based on a monolithic box resonator

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Optical parametric oscillation based on a monolithic resonator is an important way to generate a coherent laser with a narrow linewidth and a wide tunable range in a long wavelength, which can be used in spectroscopy and quantum source generation. In this Letter, we demonstrate doubly resonant optical parametric oscillation with natural phase matching based on the box resonator with Q up to 5.68×10^7. Moreover, we realized a 1-μm laser with a 1-kHz linewidth, a 200-mW output power, and a 153.94-nm wavelength tuning range. Furthermore, the monolithic box resonator has the potential to achieve a fully integrated high-power laser, and it can also be used for highly efficient spontaneous parametric down-conversion and bright narrow-band biphoton generation.

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With the advantages of lower cost and more portability, the miniature laser is gradually becoming one of the sticking points in the development of lasers and is widely used in spectroscopy [1–3], optical communication [4], etc. Optical parametric oscillators (OPOs) [5–10] are widely used for achieving a wide tuning wavelength range and producing lasers in the waveband that ordinary lasers have difficultly achieving. Benefiting from the high-quality factor and the strong optical field confinement of the optical resonator, OPOs based on the monolithic resonator are an important way to generate miniature low-threshold, narrow-linewidth lasers. Previous miniature lasers generated by the OPOs are generally based on the whispering gallery mode resonator [11–15], the microring resonator [16,17], etc. Sub-μW threshold power has been achieved in the whispering gallery mode resonator [13,14], which benefits from the high accumulated energy from the resonance of the pump, the signal, and the idler light in the resonator simultaneously. On the other hand, there exist some limitations in the specific scenario where the high output power and easy tuning method are required.

The box resonator, a newly developed Fabry-Pérot (FP) cavity fabricated by polishing and coating, shows the capability of wavelength-selective cavity enhancement while meeting the requirements of low transmission loss and miniaturization. Wavelength-selective cavity enhancement of the box resonator can help flexibly adjust the resonance wavelength and the phase-matching methods. This box resonator has achieved a $\chi^{(2)}$ optical frequency comb around the zero dispersion wavelength of the box resonator [18], which demonstrates the flexible box structure manipulation. The resonator has also realized a broadband continuously tunable laser in the mid-infrared wavelength with a sub-10-kHz linewidth [19]. To use the max $\chi^{(2)}$ nonlinear coefficiency of lithium niobate (LN), these above works both adopted periodically poling quasi-phase-matching technology, which requires the preparation of complex electrodes to realize periodically modulating the ferroelectric domain. This process compensates the mismatched phase among the interacting waves caused by material dispersion, but increases the device fabrication complexity and cost. Besides the above phase-matching method, actually there exists natural phase matching because different crystal axes of LN exhibit different refractive indexes and dispersion. We demonstrate natural phase matching on box resonator by the benefit of high-quality and small mode volumes. Besides this, compared with previous work [19], the threshold power has been greatly reduced through the principle and box structure optimization.

In this Letter, we utilize the box resonator to achieve the doubly-resonant OPOs with natural phase matching. The doubly resonant optical parametric oscillation is engineered by coating the highly reflective film at both ends of the box waveguide. Adjusting the temperature of the box resonator to around 60 °C makes the phase matching satisfied, which is free of the LN domain engineering. The quality factor (Q) of the box resonator reaches 5.68×10^7 in 1064 nm, which is close to the intrinsic material limit of LN. A 1-μm high-power laser is generated by a 532-nm pump. The tuning range from 996 to 1142 nm is achieved by adjusting the temperature, and the threshold power is 191.25 mW, which is consistent with the theoretical calculation. The fundamental linewidth of the 1-μm laser is measured by the delayed self-heterodyne interferometric linewidth (DSHI) measurement system, and the fundamental linewidth is 1 kHz. On the one hand, 1-μm miniature tunable lasers with narrow linewidths and low threshold power have a variety of practical applications, such as the Doppler lidar, sensing, etc. On the other hand, the box resonator is expected to achieve a highly efficient spontaneous parametric down-conversion source.

The structure of the box resonator is shown in Fig. 1(a). The box resonator is fabricated on the z-cut MgO-doped LN wafer, which is highly resistant to laser damage. The

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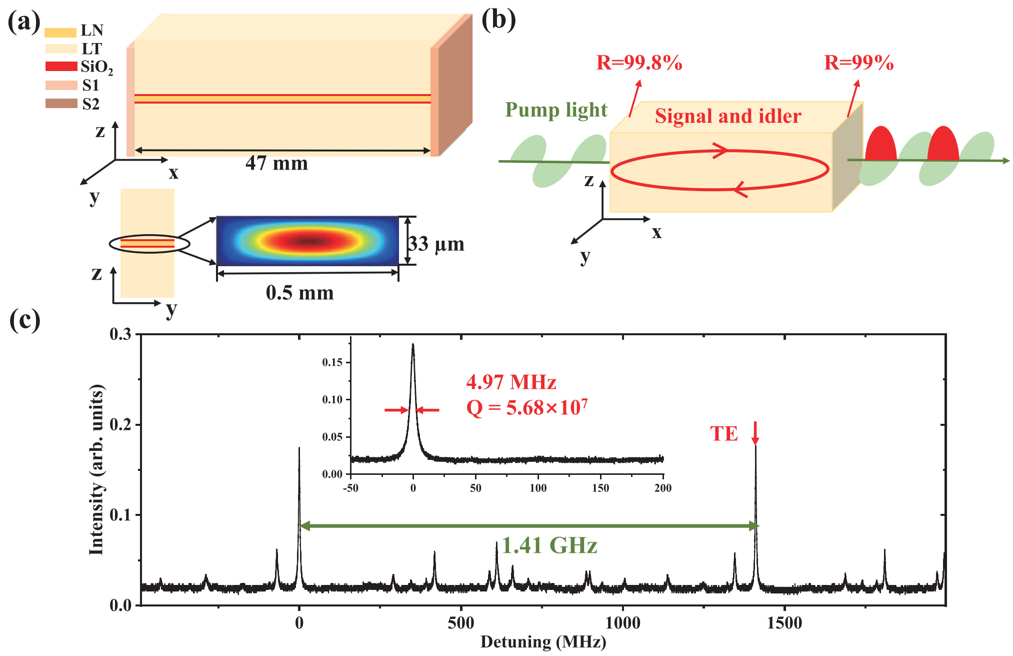

FIG. 1. (a) The schematic diagram of the box resonator structure and the mode field distribution of the resonator. (b) The principle of the experiment. (c) The transmission signal of the box resonator at around 1 μm. The free spectral range of the box resonator is 1.41 GHz. The inset shows the fitted resonance peak linewidth of the TE mode is 4.97 MHz and Q is 5.68×10^7.

33-μm-thick MgO-doped LN slice is bonded on the lithium tantalate through the 100-nm silicon oxide photoresist, which is helpful for heat conduction and convenient experimental operation. Then this sandwich structure is sliced into waveguides with a length of 47 mm and a width of 0.5 mm. After polishing the waveguide, the ends of the waveguide are coated with S1 and S2, which increase the transmittance to 100% at 0.532 μm and increase the reflectivity to 99% and 99.8%, respectively, at 1.06 μm. The developed box resonator is a miniature FP cavity and is fabricated by polishing and coating. Polishing can reduce the roughness of the sidewall and thus reduce energy transmission loss. Compared with previous work, we further reduce the thickness of LN to obtain a smaller mode field area, thereby reducing the threshold power. We can achieve the desired parametric process through high-reflection coating at both ends of the waveguide. The detailed fabrication process is introduced in Refs. [18,19].

In the experiment, we employ type-I phase matching to enable the generation of the optical parametric process without periodic poling which reduces the complexity of the experiment. The experimental principle is shown in Fig. 1(b). The anisotropy of LN enables phase matching among the pump light (e) at 0.532 μm, the signal light (o) at 1.06 μm, and the idler light (o) at 1.06 μm under the special polarization configuration of light waves. Thermal tuning of the refractive index of LN affects the wavelength of phase matching.

We characterize the quality factor of the box resonator using a continuously tunable laser (TOPTICA CTL 1050). Due to the nonlinear frequency scanning, the Mach-Zehnder interferometer is employed to generate an interference signal and calibrate the scan nonlinearity of the tunable laser. As shown in Fig. 1(c), the free spectral range of the box resonator is 1.41 GHz, which matches with the cavity length of 47 mm. The linewidth of the transverse-electric (TE) mode is 4.97 MHz, and the quality factor is 5.68×10^7, which is close to the material limit of LN and is comparable to the quality factor of the previous integrated optical resonator. High-order modes supported by the box resonator are more affected by the sidewall roughness and have higher energy transmission losses. And they correspond to other peaks in the transmission spectrum.

The specific experimental setup is shown in Fig. 2(a). The pump light of the optical parametric oscillation is the cw green laser (COHERENT Verdi-v5) with a maximum output power of 5 W, a MHz-linewidth-level laser. The combination of wave plates and a polarizing beam splitter (PBS) ensures that the pump light incident on the box resonator has transverse-magnetic polarization. The combination of multiple cylindrical lenses produces an asymmetric light spot shape that matches the mode field of the box resonator. The signal, idler, and pump light from the resonator are collimated by the plano-convex lens. The optical filter after the box resonator removes the residual pump light, and the signal light and idler light are collected into the single-mode fiber through the cage system. The box resonator is placed in a sealed double-layer metal box to precisely control the temperature of the crystal, which reduces the temperature perturbation.

For near-degenerate doubly resonant OPOs, the conversion efficiency can be expressed [20] as

$$\eta = \frac{P_{\mathrm{i,out}} + P_{\mathrm{s,out}}}{P_{\mathrm{p,in}}} = \frac{4T}{A+T}\left(\sqrt{\frac{P_{\mathrm{th}}}{P_{\mathrm{p,in}}}} - \frac{P_{\mathrm{th}}}{P_{\mathrm{p,in}}}\right),$$

where T is the external energy coupling loss coefficient and A is the energy transmission loss coefficient of the microresonator, P_{in} represents the energy coupled into the

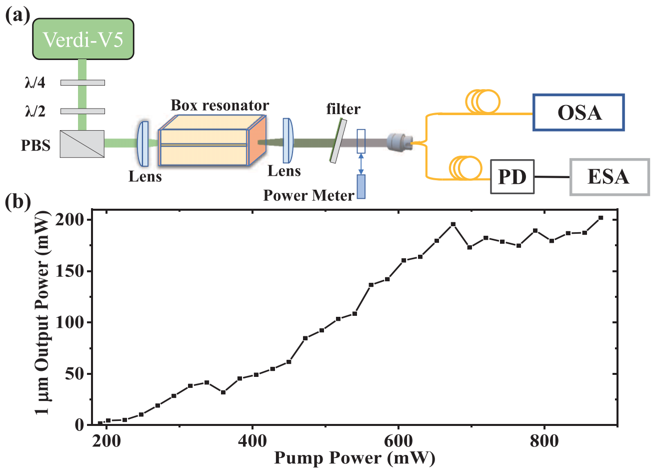

FIG. 2. (a) Experimental setup for 1-μm integrated tunable lasers. Verdi-V5, continuous-wave visible laser at 0.532 μm; PBS, polarizing beam splitter; OSA, optical spectrum analyzer; ESA, electronic spectrum analyzer; PD, photodetector. (b) The 1-μm output power as a function of pump power. The threshold power of doubly-resonant OPOs is 191.25 mW and the maximum output power exceeds 200 mW with the maximum conversion efficiency of 28.98%.

microresonator, and P_{out} represents the energy coupled out of the box resonator. The subscripts p, s, and i represent the pump, signal, and idler, respectively. As the pump power increases, the conversion efficiency first increases and then decreases. The reason is that the energy accumulation of the parametric light in the cavity enables the sum-frequency process and limits the improvement of the conversion efficiency of the optical parametric oscillation. The relationship between the output power of the signal light and the idler light and the power of the pump light is shown in Fig. 2(b). The threshold of doubly resonant OPOs is measured to be 191.25 mW. According to the threshold power measured by experiments, we can get the maximum conversion efficiency of 35.72% theoretically. When the pump power is 675 mW, we get the maximum coupling efficiency of 28.98%. There is a certain deviation between the experimental results and the theoretical results because the energy coupling coefficient of the resonator deviates from the theoretical design. The 1-μm maximum output power exceeds 200 mW.

Temperature affects the refractive index of the resonator, thereby changing the phase mismatch of the parametric process. The phase matching at specific temperature selects the longitudinal mode with the highest conversion efficiency. The signal and idler wavelengths can be tuned by varying the temperature of the box resonator. We achieved a wavelength tuning range from 992.57 to 1146.51 nm by changing the temperature from 55.64 °C to 64.09 °C [Fig. 3(a)]. The wavelength tuning range is mainly limited by the phase-matching condition and the supported wavelength range of the dielectric coating film at both ends of the box resonator together. As is shown in Figs. 3(b) and 3(c), the spectra of the signal light and the idler light are characterized by the optical spectrum analyzer. At $T = 55.64$ °C, the optical parametric oscillation is in a nearly degenerate state. Limited by the resolution of the spectrometer, the linewidth of the signal light and the idler light is difficult to characterize.

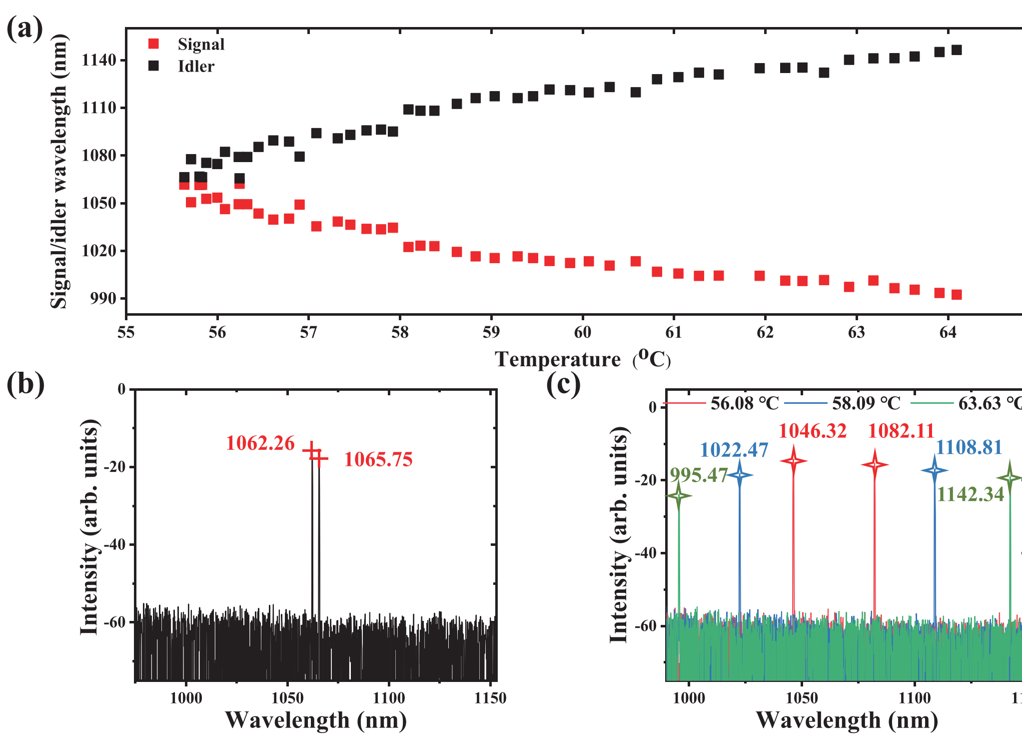

FIG. 3. (a) Wavelengths of the signal and idler lights as a function of temperature. A specific temperature supports only one phase-matching case—one pair of signal and idler beams. (b) and (c) The spectra of signal light and idler light in $T = 55.64$ °C and $T = 56.08$, 58.09, and 63.63 °C.

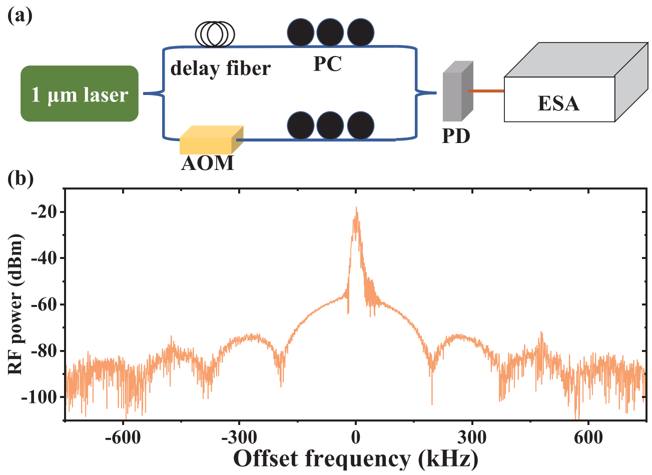

FIG. 4. (a) The system diagram of the delayed self-heterodyne linewidth measurement. AOM, acoustic-optic modulator; PC, polarization controller; PD, photodetector; ESA, electronic spectrum analyzer. (b) The measured coherence envelope obtained from heterodyne interferometry with 1 km delay fiber, showing a CDSPST of 20.1 dB. The corresponding beat frequency linewidth is 1 kHz.

The linewidth determines the spectral resolution and coherence of the laser. Lasers with a narrow linewidth have a wide range of applications in optical communications [21], high-precision spectroscopy [22,23], and optical sensing [24]. As is shown in Fig. 4(a), we build a DSHI measurement system [25,26], which contains an unbalanced Mach-Zehnder interferometer, a 1-km delay fiber, and an acoustic-optic modulator (AOM). The output 1-μm laser is divided into two paths in the measurement system. One passes through a 1-km-long delay fiber, and the other passes through the AOM to generate a 200-MHz frequency shift. The light in two paths is coherently superimposed through the optical fiber coupler, and the coherent signal is detected by the photodetector and the electronic spectrum analyzer. The broadened Lorenz signal with side frequency fluctuations is displayed in the electronic spectrum analyzer [Fig. 4(b)]. The contrast difference between the second peak and the second trough (CDSPST) of the coherent envelope is

$$\Delta S(\Delta f) = 10\log_{10}\left(\frac{\left[1+\left(\frac{2c}{n\Delta f L}\right)^2\right]\left[1+\exp\left(-2\pi\frac{n\Delta f L}{c}\right)\right]}{\left[1+\left(\frac{3c}{2n\Delta f L}\right)^2\right]\left[1-\exp\left(-2\pi\frac{n\Delta f L}{c}\right)\right]}\right),$$

where c and n are the speed of light and the effective refractive index, L represents the length of the delay fiber, and Δf represents the Lorentzian linewidth. The CDSPST is related to the linewidth of the laser. Therefore, we calculate the CDSPST of the coherent envelope of the power spectrum is 20.1 dB and predict the fundamental linewidth of the 1-μm laser is 1 kHz [Fig. 4(b)].

In this Letter, we achieved a 1-μm miniature laser with natural phase matching on the monolithic box resonator. With near material-limited quality and a small mode field, a 191.25-mW OPO threshold is achieved even without quasi-phase-matching. In this work, doubly resonant OPO is achieved around 60 °C, with a 200-mW max output power, a 154-nm tuning range, and a 1-kHz linewidth. This Letter also has important research value in quantum optics. A monolithic box resonator with low transmission loss and high conversion efficiency has been realized in our work and can be used as a highly efficient spontaneous parametric down-conversion source when the pump power is far below the threshold of the OPOs. It has a wide range of applications in the generation of entangled photon pairs, quantum communication, etc.

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