An on-chip tunable micro-disk laser fabricated on Er$^{3+}$ doped lithium niobate on insulator (LNOI)

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We demonstrate a C-band wavelength-tunable microlaser with an Er$^{3+}$ doped high quality (~$1.02 \times 10^6$) lithium niobate microdisk resonator. With a 976 nm continuous-wave pump laser, lasing action can be observed at a pump power threshold as low as ~250 μW at room temperature. Furthermore, the microdisk laser wavelength can be tuned by varying the pump laser power, showing a tuning efficiency of ~-17.03 pm/mW at low pump power blow 13 mW, and 10.58 pm/mW at high pump power above 13 mW.

1. INTRODUCTION

Featured by its broad optical transparency window (0.35-5 μm), high nonlinear coefficient ($d_{33} = -41.7 \pm 7.8 \text{ pm/V@}\lambda = 1.058 \mu\text{m}$), high refractive index (∼2.2), and large electro-optical effect ($r_{33} = 30.9\text{ pm/V@}\lambda = 632.8\text{nm}$), lithium niobate on insulator (LNOI) is a promising material platform for photonic integrated circuit (PIC) [1-3]. So far, a variety of LNOI-based PIC devices have been demonstrated including electro-optic modulators, nonlinear optical devices, and quantum optical devices which have made strong impacts on a wide range of applications ranging from optical communications, microwave photonics and quantum optics to optical computing and metrology [4-9]. All of these LNOI PIC devices are demonstrated with external light sources. It is highly desirable to realize on-chip generation and integration of light sources into the LNOI PIC devices which enables more compact, more efficient, and more stable PIC devices. For this reason, it is of vital importance to realize on-chip microlasers with a wavelength tunability on the LNOI substrate. It should be noted that so far C-band microlasers based on microresonator have been successfully fabricated in indium phosphide (InP), indium arsenide (InAs), Er$^{3+}$-doped silica by photolithography methods [10-18]. Unlike these materials, high quality (Q) LNOI-based microresonators have only been demonstrated recently [19-23]. Here, we demonstrate a C-band microlaser on an Er$^{3+}$-doped LNOI chip. The diameter of the LN microdisk is 200 μm. The microdisk resonator is pumped at 976 nm through a tapered optical fiber and the lasing threshold is 250 μW at room temperature. The low threshold is result of the high cavity optical Q (∼$1.02 \times 10^9$), which leads to a large intracavity pump intensity. We also observed a laser wavelength tuning efficiency of ~$17.03 \text{ pm/mW}$ at low pump power below 13 mW, and $10.58 \text{ pm/mW}$ at high pump power above 13 mW.
2. DEVICE FABRICATION

In our experiment, the on-chip Er\textsuperscript{3+}-doped LN microdisk was fabricated on an Er\textsuperscript{3+} doped Z-cut LN thin film wafer with a thickness of 600 nm. A 3-inch Er\textsuperscript{3+} doped LN wafer (concentration of Er\textsuperscript{3+} ions ~1 mol\%) which is purchased from Shanghai Dahong Optics and Fine Mechanics Co., Ltd was ion sputtered onto a LN thin film with a thickness of 600 nm by Jirun NANOLO Co., Ltd. The Er\textsuperscript{3+} doped LN thin film was bonded onto a silica layer with a thickness of ~2 μm, and the silica layer was grown on a 0.5 mm thick undoped crystalline LN substrate [24]. As shown in Fig. 1(a), although the undoped LN wafer appears almost colorless, the Er\textsuperscript{3+} doped LN wafer appears reddish. The configuration of Er\textsuperscript{3+}-doped LN-on-insulator (Er\textsuperscript{3+}-LNOI) was shown in Fig. 1(b), on top of which a 600-nm-thickness layer of chromium (Cr) film was deposited by magnetron sputtering method. The fabrication process includes five steps, as illustrated in Fig. 1(c)-(f). First, the Cr film on the Er\textsuperscript{3+}-LNOI sample was patterned into a disk-shaped mask using space-selective femtosecond laser (PHAROS, LIGHT CONVERSION Inc.). Subsequently, the chemomechanical polishing (CMP) process was performed to fabricate the LN microdisk by a wafer lapping polishing machines (NUIPOL802, Kejing Inc.). In this step, the LN film underneath the Cr mask can be preserved whereas the LN in the opening area is completely removed. The CMP process allows to create a LN microdisk with extremely smooth rim for high Q factors. Then, the Cr thin film was removed with a chemical wet etching process and a secondary CMP process was performed for thinning the LN disk as well as cleaning the ablation debris on the disk surface. Finally, the fabricated structure was immersed in a buffered hydrofluoric acid (HF) solution to partially etch the silica layer into the shape of a pillar supporting the LN microdisk. It takes about 2 hours in total to produce the device. More details about the LN microdisk fabrication can be find in Ref. 21-23.

The energy level diagram of the Er\textsuperscript{3+} ions as well as the absorption and the emission transition is depicted in Fig. 3(a). It has been established that the intermediate state \(4I_{11/2}\) and the \(4F_{7/2}\) state can be accessed through resonantly excitation and excited state absorption with the pump laser at 976 nm, respectively. The \(4I_{13/2}, 4S_{3/2}, \) and \(4I_{15/2}\) states can be populated by the effective nonradiative relaxations of the \(4F_{7/2}, 4I_{11/2}\) and \(4I_{13/2}\). The fluorescence emissions at ~530 nm, ~550 nm in Fig. 3(b) and that at ~1550 nm in Fig. 3(c) can be attributed to the transitions of \(4I_{11/2} \rightarrow 4I_{13/2}, 4F_{5/2} \rightarrow 4I_{13/2} \) and \(4I_{13/2} \rightarrow 4I_{15/2}\), respectively [25]. As shown in Fig. 3(b) and (c) with very slight pump power at the wavelength of 976 nm. The abundant fluorescence lines indicate that the ion concentration of the Er\textsuperscript{3+} doped LN microdisk is sufficiently high for generating lasers if strong pump laser is applied.

Fig. 4(a) shows a typical pump and laser emission spectrum collected in the 800-1670 nm spectral range. Clearly, the wavelength of the pump is ~976 nm and the laser emission is observed at ~1560 nm. The inset in Fig. 4(a) displays the strong green upconversion fluorescence of the microdisk, which was taken using a CMOS camera (DCC3240C, Thorlabs Inc.) mounted onto an optical microscope. The optical beam path of the pump laser in the microdisk can clearly be seen in the inset of Fig. 4(a). Fig. 4(b) is the enlarged spectrum near 1560 nm, featuring several laser lines at the C-band telecommunication wavelengths. The lasing threshold can be determined by integrating the intensity of the emission lines over the 1560-1567 nm spectral range and plotting the...
integrated laser intensity as a function of the pump laser which is dropped into the cavity, as shown in Fig. 4 (c). The lasing threshold is observed around 250 μW, and a linear behavior is observed above the threshold.

Fig. 3 Fluorescence spectra under 976 nm pump. (a) Schematic of the energy level diagram of the Er³⁺ ions as well as the absorption and the emission transition. (b) Visible upconversion and (c) infrared downconversion emission spectra of the Er³⁺-doped LN microdisk.

The lasing mode of the Er³⁺-doped LN microdisk shows a strong dependence on the pump laser power. As shown in Fig. 5(a), at the pump laser power of 23.1mW, the laser behaves like a single frequency lasing emission at the wavelength around 1551 nm accompanied with several weak satellite emission lines. This should be a result of the strong competition between the lasing modes of different gain efficiencies.

It is well known that the high optical intensity inside the LN microdisk, can lead to both significant photorefractive and thermo-optic effects [26-28], which provides us an opportunity to efficiently tune the laser wavelength merely by changing the pump laser power. As shown in Fig. 5(b), the quasi-single frequency lasing wavelength can be tuned smoothly with the increasing pump power. When the input pump power increases from 4.05 mW to 9.8 mW, blue-shift of laser wavelength is observed, indicating that the photorefraction effect plays a leading role for resonance shift. The photorefractive effect manifests itself with a decrease of the refractive index depending on the optical intensity inside the microdisk. When the input power increases further from 17.7 mW to 40.6 mW, red-shift of the laser wavelength is observed. This implies that the thermo-optic effect plays the leading role at high pump intensity. To determine the tuning efficiency, the lasing spectra of the Er³⁺-doped LN microdisk were recorded at various input powers as shown in Fig. 5(c). A linear dependence of the emission wavelength on the pump power is observed, showing a tuning efficiency of 17.03 pm/mW for low pump powers blow 13 mW (corresponding to -2123 GHz/mW), and 10.58 pm/mW for high pump power above 13 mW (corresponding to 1.319 GHz/mW). The observation indicates that the Er³⁺-doped LN microdisk laser provides an efficient and convenient method for all optical tuning of the on-chip laser wavelength.

4. CONCLUSION

In summary, we demonstrate an Er³⁺ doped LN microdisk C-band laser on a lithium niobate thin film chip. A tuning efficiency of ~17.03 pm/mW is observed at low pump power blow 13 mW, whereas the tuning efficiency dramatically changes to ~10.58 pm/mW at high pump power above 13 mW. The LN microdisk laser can be integrated with other nanophotonics structures to construct LNOI-based PIC devices to serve as an on-chip tunable laser source.

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