Proc. Conference on Laser and Electro-Optics (CLEO 2005)
Baltimore, May 2005, paper CML1

Integrated Optical Parametric Oscillators with Ti:PPLN Waveguides

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Abstract: The state of the art of integrated optical parametric oscillators with Ti-indiffused waveguides in Periodically Poled Lithium Niobate (PPLN) is reviewed with emphasis on devices for the mid infrared spectral range (2700 nm < $\lambda_{s,i}$ <3500 nm).

OCIS codes: (130.4310) Nonlinear integrated optics, (190.4970) Parametric oscillators and amplifiers

Integrated optical parametric oscillators (IOPOs) are attractive devices to generate tunable coherent radiation in a broad wavelength range with many applications mainly in environmental sensing and process monitoring. In comparison to their bulk counterparts IOPOs promise a lower oscillation threshold, a higher stability with respect to ambient fluctuations and guarantied spatial single mode emission. Moreover, there is a great potential to monolithically integrate (intracavity) components such as electro- and acoustooptical tunable filters, phase and amplitude modulators, Bragg reflectors as wavelength selective mirrors, wavelength-dependent couplers to get separate cavities for signal and idler, (tunable) pump lasers in the same structure, etc. Lithium Niobate and in particular periodically poled Lithium Niobate (PPLN) to exploit quasi phase matching (QPM) proved to be the most attractive substrate material to develop IOPOs. Using Ti-indiffused waveguides very low propagation losses (down to 0.03 dB/cm in the mid infrared (MIR) spectral range) have been achieved, enabling the development of waveguide resonators of very high quality. Contrary to proton exchanged (pe) waveguides Ti:PPLN waveguides have nearly no absorption around 2700 nm wavelength due to the excitation of OH-vibrations. For that reason Ti:PPLN waveguides are the preferred candidates for MIR-IOPOs.

Ti-doped waveguides are fabricated by an indiffusion of vacuum deposited Ti-stripes at temperatures in the range 1000 °C < T < 1100 °C, where ferroelectric domains are no longer stable. Therefore, it is not possible to define the waveguide structures in a PPLN substrate; it is necessary to perform the Ti-indiffusion first and to generate the domain structure afterwards. To be specific, up to 94 mm long, periodically poled, straight Ti:$LiNbO_3$ waveguides of 18, 20 and 22 μm width have been fabricated in 0.5 mm thick and 12 mm wide Z-cut, X-propagation $LiNbO_3$ substrates using the standard indiffusion technology. Subsequently, ferroelectric domain patterns with a periodicity Λ of about 31 μm have been realized by electric field assisted poling. Moreover, for the first time up to 200 mm long, periodically poled, partially bent waveguides have been developed to increase the interaction length; the 180° waveguide bends have radii from 22 to 36 mm. The propagation losses of the straight waveguides can be as low as 0.03 dB/cm in the MIR; those of the bent sections approach 0.1 dB/cm in the channels of largest radius. To set up resonators external dielectric mirrors on a sapphire substrate have been clamped to the waveguide end faces. Alternatively, using ion beam assisted evaporation dielectric MIR-mirrors with up to 12 quarter-wave layers of SiO_2 and TiO_2 have been deposited on the waveguide end faces. An example of a corresponding spectral mirror characteristic is shown in Fig. 1; the reflectivity above 2700 nm wavelength approaches 99 %, whereas in the pump band around 1550 nm a residual reflectivity < 20 % remains. Depending on waveguide parameters, pump wavelength and mirror characteristics singly or doubly resonant parametric oscillation is achieved [1].

Before mirror deposition (stimulated) MIR optical parametric fluorescence (OPF) was investigated in both types of waveguides. Fig. 2 shows as an example the tuning characteristics of the signal and idler waves generated in a straight, 94 mm long, 22 μm wide waveguide of 31.52 μm domain periodicity. The coupled (cw) pump power was approximately 300mW. The MIR-OPF was continuously tunable from 2750 to 3475 nm by adjusting the pump wavelength from 1535 nm to 1596 nm. The calculated phase matching curve shows excellent agreement with the measured results. (In waveguides of larger domain periodicity the tuning characteristics shifts as a whole to the left. The same happens, if broader waveguides or higher temperatures are used). Moreover, selected spectral characteristics are given in Fig. 2 together with the calculated responses; the differences originate from residual, small waveguide inhomogeneities. The longer the OPF wavelength, the noisier the spectrum is arising from the weaker efficiencies of monochromator and detector. All peaks become broader with increasing pump wavelength in good agreement with modelling results [2].

Experimental room temperature data of the total OPF output power (signal and idler) from another sample (Λ = 31.44 µm; w = 20 µm; L = 94 mm) are also shown in Fig. 2 as function of the pump power in a pulsed mode of operation (λ_p = 1552 nm, λ_s = 2850 nm, λ_i = 3400 nm); the pulse repetition rate was 1 MHz. The transition to a strong exponential rise (corresponding to high parametric amplification) at high pump power levels can be clearly observed; it is in excellent agreement with the theoretical response, which is fitted by just one parameter.

Using external mirrors with reflectivities > 95 % in the wavelength range 2800 nm < λ < 3400 nm doubly resonant parametric oscillators have been set up with straight Ti:PPLN channel guides. The best device had a threshold of only 14 mW incident pump power (λ_p = 1541.5 nm), corresponding to about 10 mW coupled to the fundamental waveguide mode. A continuous tuning range of 2804 nm < λ < 3379 nm has been demonstrated by tuning the pump wavelength from 1532 nm to 1570 nm; the maximum output power was about 8 mW. The fine tuning behaviour is not only determined by the phase match condition, but also by the double resonance condition for signal and idler. This leads to a sawtooth spectral dependence of about 180 GHz spectral width for e.g. the signal frequency as function of the pump frequency, well known from bulk OPOs.

The total output power (signal and idler) versus pump power of the first doubly resonant IOPO with dielectric mirrors vacuum-deposited on the waveguide end faces is shown in Fig. 3; the waveguide parameters are given in the inset. The pump wavelength is λ_P = 1565 nm, resulting in a signal (idler) wavelength of 2988 nm (3286 nm). The oscillation threshold of 150 mW is much higher than that of previous oscillators with external mirrors. However, this is not a consequence of the dielectric mirrors, but of the higher waveguide losses of this particular sample. The corresponding theoretical result predicts a threshold of 50 mW (see Fig. 3). If we take into account that the calculated output power is plotted versus the coupled pump power (coupled to the fundamental mode), but the measured output is plotted versus the incident pump power (the coupling coefficient to the fundamental mode can only be estimated to be around 50 %) a relatively good agreement is found between experimental and theoretical results.

Using external mirrors with reflectivities > 95 % in the wavelength range 3200 nm < λ < 3800 nm (but < 5 % in the range 2650 nm < 2980 nm) singly resonant IOPOs have been realized. The oscillation threshold of the best device was 275 mW incident pump power in good agreement with the modelling results. At a pump power of 1.25 W a MIR output (λ_s = 2883 nm, λ_i = 3364 nm) of 300 mW has been achieved. Due to the singly resonant configuration of the oscillator the signal power always exceeds the idler power considerably. The output wavelength could be tuned within the range 2720 nm < λ_s, λ_i < 3500 nm by changing the pump power wavelength from 1530 nm to 1580 nm; the linewidth of the emission can be below 170 MHz (our resolution limit) corresponding to single frequency emission. Singly resonant devices with mirrors vacuum deposited on the waveguide end faces have not yet been fabricated.

In conclusion, the state of the art of (MIR-) IOPOs with Ti:PPLN waveguides was reviewed. Due to their very low threshold doubly resonant devices can be pumped by a semiconductor laser diode alone without additional amplification and operated at room temperature in a cw mode. The first doubly resonant MIR-IOPO with dielectric mirrors deposited on the waveguide end faces has been reported; there is still a large potential to improve its properties. Singly resonant IOPOs are attractive candidates for high resolution spectroscopy; they offer nearly continuous tuning of the emission wavelength and an extremely narrow linewidth. More complex IOPOs with additional intracavity components such as wavelength splitters and phase shifters will be developed in the future to obtain true continuous tuning.

The authors gratefully acknowledge the support of this project within the programme of the research unit "Integrated Optics in Lithium Niobate" by the Deutsche Forschungsgemeinschaft (DFG).

[1] G. Schreiber, D. Hofmann, W. Grundkötter, Y. L. Lee, H. Suche, V. Quiring, R. Ricken, and W. Sohler, "Nonlinear integrated optical frequency converters with periodically poled Ti:$LiNbO_3$ waveguides", Proc. SPIE, vol. 4277, pp. 144-160 (2001), Photonics West 2001, paper 4277-18 (invited).

[2] W. Grundkötter, Ph.D. thesis, University of Paderborn, to be published in 2005

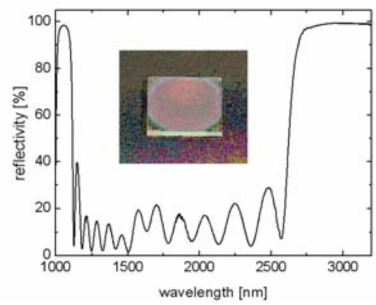

Fig. 1. Reflectivity of the dielectric cavity mirrors of a doubly resonant MIR-IOPO versus wavelength.

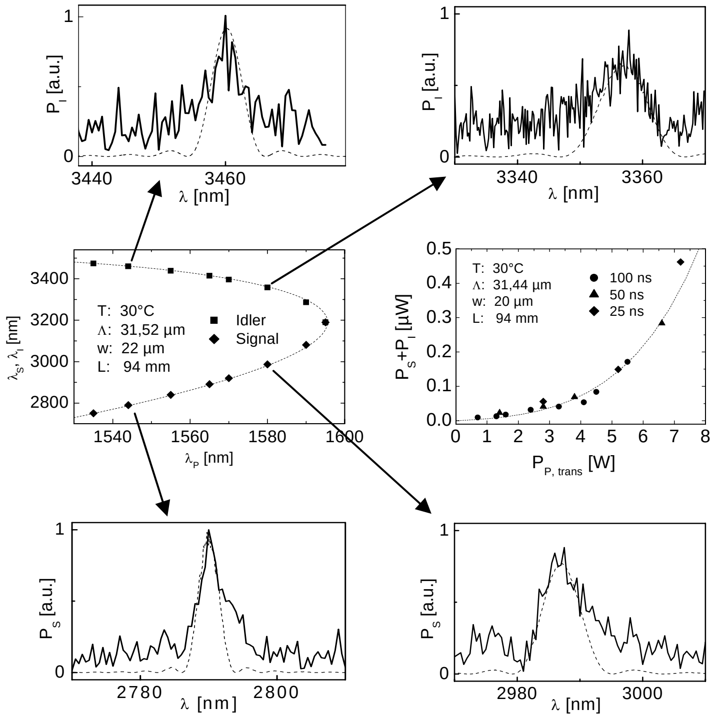

Fig. 2. Measured (filled squares) and calculated (dotted line) tuning characteristics of OPF as signal and idler wavelengths versus the pump wavelength in cw-operation. (left diagram in the middle). Selected experimental (straight lines) and theoretical (dotted lines) spectral characteristics of the fluorescence are shown in the upper and lower diagrams. Total OPF output power versus transmitted pump power (λ_p = 1552 nm) in a pulsed mode of operation (1 MHz. repetition rate).

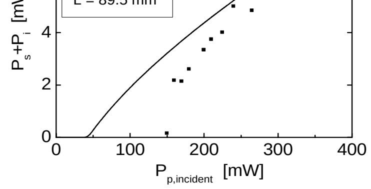

Fig. 3. Sum of signal (λ_s = 2988 nm) and idler (λ_i = 3286 nm) output power of the first IOPO with dielectric mirrors vacuum deposited on the waveguide end faces as function of the pump wavelength (λ_p = 1565 nm).