CW, Broadly Tunable, Red, Green and Blue Light Generation in Aperiodically Poled Zn-Diffused $LiNbO_3:Er^{3+}/Yb^{3+}$ Channel Waveguides

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In this work, the CW broadly tunable simultaneous generation of the primary colors, red, green and blue in aperiodically poled Zn-diffused $LiNbO_3:Er^{3+}/Yb^{3+}$ channel waveguides is presented. The red and green emissions arise from energy transfer and up-conversion mechanisms between Yb^{3+} and Er^{3+} ions, while the blue light is produced by quasi-phase matching processes.

Keywords: second harmonic generation, non-linear waveguides, Zn-diffusion, up-conversion, rare earth, lithium niobate

Introduction

The modulation, periodic or aperiodic, of the non-linear coefficients offer the possibility of obtaining non-linear frequency conversion via quasi-phase matching (QPM) [1,2]. The large effective non-linear coefficient of lithium niobate ($LiNbO_3$) compares favourably with that of other ferroelectric crystals [1,3].

Several non-linear devices based on $LiNbO_3$, in which the periodic modulation is combined with the high power densities available in waveguiding structures have been reported [4]. Zn-diffusion from the vapor phase [5], represents an alternative waveguide fabrication technique to produce low-loss optical waveguides in $LiNbO_3$ in which the initial ferroelectric domain patterns of the substrate are preserved [6]. It has been also reported that the waveguides prepared by this technique exhibit a high optical damage resistance [7] highly useful to sustain stable operation, in continuous wave regime, in RGB integrated devices.

In this work, APPLN crystals have been grown adding erbium and ytterbium oxides to the initial melts by using the appropriate growth conditions [8]. A *y*-cut wafer has been used to fabricate Zn-diffused APPLN channel waveguides in which second harmonic generation in the blue spectral range has been explored. A high stability in the generation of blue light has been found, even under continuous wave operation at room temperature. Red and Green emissions can be also achieved using up-conversion processes between Er^{3+} and Yb^{3+} ions leading finally to CW simultaneous generation of Red, Green and Blue light.

Experimental Procedure, Results and Discussion

APPLN crystals were grown by the off-centered Czochralski method, along the *a*-axis, with automatic diameter control by crucible weighing system. The initial melts containing the congruent $LiNbO_3$ ([Li]/[Nb] = 0.945), were doped with erbium (0.5 mol %) and ytterbium (0.5 mol %) oxides with a purity grade of 99.99%. The growth conditions, pulling and rotation rates and seed crystal shift, were adjusted appropriately to favor the formation of modulated ferroelectric domain distributions [9].

A *y*-cut wafer from the APPLN crystals, in which the ferroelectric domain distribution was previously characterized, has been used to fabricate the channel waveguides by the Zn-diffusion

technique following a two-step process (exchange and diffusion) [5,10]. It was shown that this waveguide fabrication process does not alter the domain distribution in the crystal [6], being compatible with rare earth doped congruent lithium niobate [7,11].

When the light from a Ti:Sapphire laser (operating at 920 nm) was coupled into the channels by using the end-fire coupling technique a strong green emission is observed. However when the output is spatially separated by using a dispersive prism, four intense spots can be seen even by the naked eye, Figure 1. From right to left, blue, green, and red colors are clearly distinguished, besides an additional spot coming from the IR pump beam, which appears as "white" due to saturation effect of the imaging device.

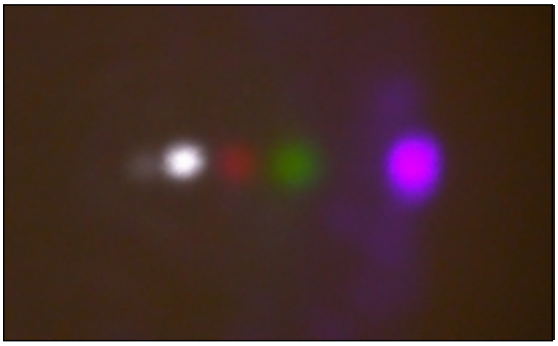

Figure 1.- Photograph of the output waveguide focused on a screen, after passing a dispersive prism, showing the three fundamental colors, besides the spot coming from the infrared pump at 920 nm.

In order to investigate the origin of the three fundamental colors produced in the channel waveguide by infrared pumping, the waveguide output was focused on the entrance slit of a monochromator, and the dispersed light was detected by using a photomultiplier tube. Figure 2(a) shows the emission spectrum from the waveguide in the visible range (450-700 nm). As it can be appreciated, the output light is the combination of two broad emissions bands in the red and in the green, and a narrow line in the blue.

The blue emission (right spot on Figure 1) is due to SHG in the non-linear channel waveguide. The experimental configuration used in the measurements, crystal axis and polarization of the incident and output beams, has been sketched in Figure 2(b). As it is indicated, only when the fundamental wave is coupled as extraordinary wave (TE propagating mode) an output narrow blue emission is detected. The blue light exhibits the same polarization as the incident ω-wave as well as the expected quadratic dependence for a second order process indicating that the frequency conversion process involves the d_{33} non-linear coefficient of $LiNbO_3$. The aperiodic ferroelectric domain distribution of the substrate provides a big set of reciprocal vectors for quasi-phase matching compensation (QPM) between the ω-wave and the 2ω-wave [11]. As a consequence, the SH signal exhibits a broadly tunable band at the expense of peak efficiency [12]. In Figure 2(b), the blue light obtained for a discrete set of fundamental wavelengths in the channel waveguide under study (4 μm width and 1 cm length) is presented. As it can be appreciated, the maximum efficiency in the frequency conversion is obtained for fundamental wavelengths around 970 nm (2ω-wave at around 485 nm).

The red and green emission bands, presented in Figure 2(a), are mainly due to the presence of energy transfer up-conversion mechanisms (ETU) involving the Er^{3+} and Yb^{3+} ions [12]. As it has been recently reported [13], the sensitization of $LiNbO_3$:Er^{3+} with Yb^{3+} ions opens an extra path for the population of the $^4F_{9/2}$ erbium level being the red emission enhanced, relative to the green one, nearly in an order of magnitude. The inset in Figure 2(a) shows the ratio between the red and green intensities measured in co-doped samples with fixed Er^{3+} concentration (0.5 mol %) and variable

Yb^{3+} concentration. As the green and red emissions are induced by ETU processes from Yb^{3+} ions, the broad and intense absorption bands of these ions (880-1040 nm) can be used to tune efficiently both erbium emissions ($^2H_{11/2}$:$^4S_{3/2} \rightarrow {}^4I_{15/2}$ and $^4F_{9/2} \rightarrow {}^4I_{15/2}$ transitions). The dependencies on pump power of both emissions, green and red, were found to be lower than the expected quadratic law. This fact could be related with the presence of saturation effects or due to the presence of the several population paths: the energy transfer processes from Yb^{3+} ions and the direct absorption of the blue light within the Er^{3+} ions ($^4I_{15/2} \rightarrow {}^4F_{5/2,\,3/2}$ absorption band).

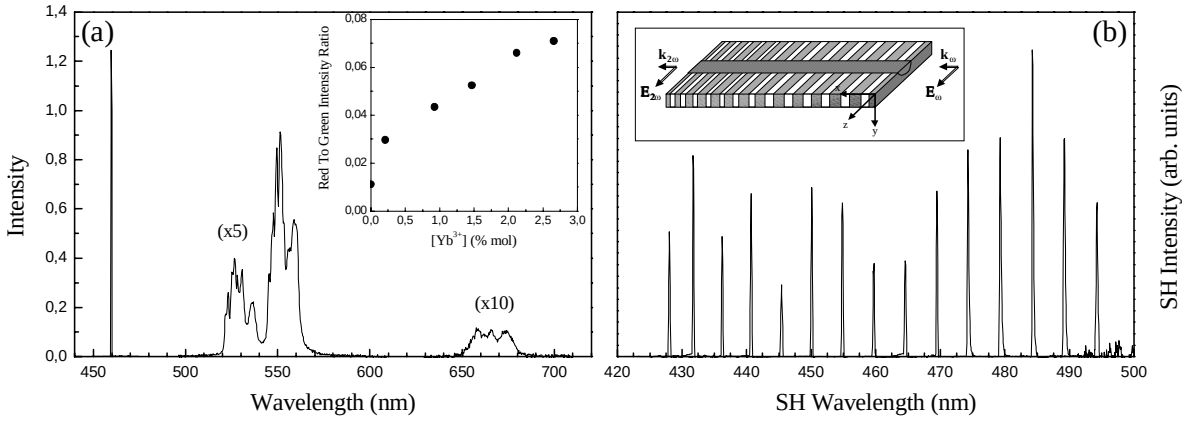

Figure 2.- (a) Emission spectrum measured in the channel waveguide after pumping at 920 nm. The inset shows the ration between the red and green intensities measured in the co-doped samples. (b) Blue SHG for a discrete set of fundamental wavelengths between 850 nm and 990 nm. The inset shows the experimental configuration used in the measurements.

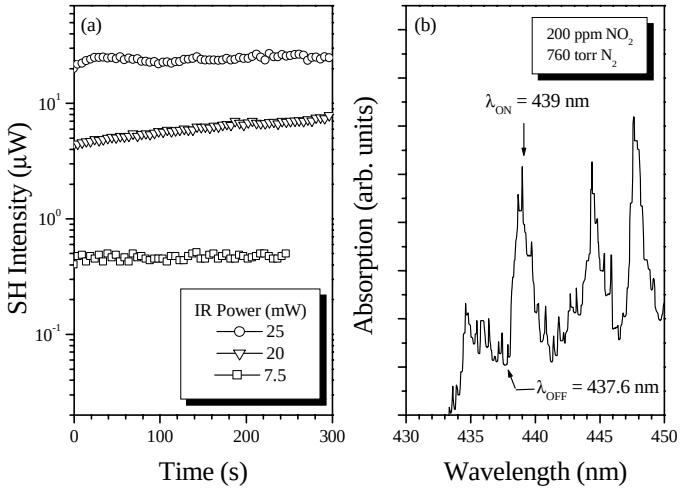

Figure 3.- (a) Evolution of the blue second harmonic, at 485 nm, measured in the Zn-diffused APPLN channel waveguide as function of time and pump power. (b) Absorption spectrum of NO_2 gas in N_2 atmosphere at a pressure of 760 torr.

It should be remarked that the channel waveguide sustains stable operation without intensity fluctuations induced by the presence of high power beams. Figure 3(a) shows the SH signal, measured at the maximum efficient peak (485 nm), as function of time for different pump powers.

The highest blue intensity propagated in the channel waveguide was found to be 20 μW corresponding to the maximum infrared pump power coupled into the waveguide, 25 mW. As it can be appreciated in the figure, the optical damage threshold is highly enough to sustain the stable SHG in the blue spectral range, even under CW conditions at room temperature.

The characteristics reported in this work, tuning range and temporal stability, are interesting features for the development of useful integrated optical sensors. In particular, the presence of some toxic gases can be detected by applying conventional absorption techniques. Such is the case of NO_2 whose absorption band, shown in figure 3(b), overlaps completely with the tuning range of figure 2(b). The concentration can be estimated by comparing the attenuation of the SH intensity by measuring at two different wavelength in the absorption spectrum, λ_{ON} and λ_{OFF} at 439 nm and 437.6 nm respectively (Differential Optical Absorption Spectroscopy [14]).

Conclusions

APPLN crystals have been grown by the off-centered Czochralski method by adding erbium and ytterbium oxides to the melt. The simultaneous, CW, RGB generation in Zn-diffused Er^{3+}/Yb^{3+} co-doped APPLN channel waveguides have been obtained. The red and green colors are produced by up-conversion processes between the Er^{3+} and Yb^{3+}ions while the blue one is generated by SHG involving the d_{33} non-linear coefficient of $LiNbO_3$. The optical damage threshold of the Zn-diffused APPLN channel waveguides was found to be highly enough to sustain the stable visible light generation, even in the continuous wave regime at room temperature.

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