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Generation of Shear Waves in a Soft Medium Using an OPO That Emits 2.1 μm Wavelength as Light Source

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Abstract

We present a scheme for conversion of pulsed light from 1.06 to 2.1 μm using a periodically poled ferroelectric crystal within a resonant cavity in which Optical Parametric Generation (OPG) nonlinear optical process occur when pumped with a pulsed Nd:YAG laser. This device emits 9 ns pulses of over 300 μJ and is a viable source for use with PhS-OCT system for generation of shear waves in a soft medium.

Keywords: Optical coherence tomography; Optical Parametric Generation; Shear Waves; nonlinear optical process; IR spectrophotometer

Introduction

Optical coherence tomography (OCT) is a noninvasive technique capable of imaging tissue microstructure at high spatial resolution [1]. PhS-OCT is an OCT based technique which can be used to detect surface acoustic waves propagating on skin and cornea surfaces, leading to quantification of the elasticity of underlying tissues [2]. For generating shear waves propagating within a soft medium a piezoelectric actuator are used [3].

Because tissue presents high absorption for electromagnetic waves at ~2 μm wavelength, in this work we propose a simple device that emits nanosecond pulses at a wavelength of 2.1 μm as an alternative for shear wave's generation. This device is based on a periodically poled ferroelectric crystal pumped with aNd:YAG pulsed laser source to obtain the emission. The conversion from 1.06 to 2.1 μm was achieved by optical parametric generation (OPG) at degeneracy point where signal wave with 2128 nm wavelength was generated.

Design of the Source of Radiation

The simplest parametric process which occurs inside a nonlinear medium is the optical parametric generation where energy from an input pump wave with angular frequency ω_p is transferred to two output waves of different angular frequencies named signal ω_S and idler ω_i while optical energy is always conserved and so $\omega_p=\omega_S+\omega_i$. According to quantum mechanics in this process a single high energy photon is splitted by a nonlinear medium into two low energy photons.

This kind of nonlinear phenomena combined with quasi-phase matching technique is very useful because we can design a periodically (or aperiodically) poled ferroelectric crystal to obtain an emission like lasers but with any desired wavelength. To increase the conversion efficiency from the pump beam to the signal or to the idler beam a resonant cavity can be used but energy of non-desired beam is "wasted".

For ourwork we convert pulses from 1064 nm to 2128 nm with quasi-phase matching technique obtained with a periodically poled lithium niobate crystal (PPLN) pumped with aNd:YAG laser source. We designed a crystal with ferroelectric domains such it produces optical parametric generation at the degeneracy point, i.e., the signal and idler wavelengths are the same so $\omega_s=\omega_i=\omega_p/2$ and then $\lambda_p=2128$ nm, twice the wavelength of pump source.

Let A_P and A_S be the electric field amplitudes of the pump and signal waves with angular frequencies of ω_P and ω_S and K_P and K_S their corresponding wave vectors where the magnitudes of this wave vectors are given by K=ωn/c, being *n* the refraction index and *c* is the speed of light. Assuming that the two waves are co-propagating along the same direction we can deduce the coupling among the waves from well-known Maxwell's equations:

$$\frac{d}{dz}A_s = i\frac{\omega_s}{n_s c}\chi^{(2)}(z)A_p A_s^* e^{i\Delta k} \quad (1)$$

$$\frac{d}{dz}A_p = i\frac{\omega_p}{2n_p c}\chi^{(2)}(z)A_s^2 e^{-i\Delta k}, \quad (2)$$

where n_p and n_s are the refractive indices of the pump and signal waves, z is the distance along the propagation direction of the waves, $\chi^{(2)}(z)$ is the spatially-varying nonlinearity of the medium and Δk is the propagation constant mismatch of the optical parametric generation process given by

$$\Delta k = k_p - 2k_s \quad (3)$$

This propagation constant is non-zero and therefore this limits the coupling of the fields which consequently reduces conversion efficiency. To increase the coupling efficiency, the nonlinearity $\chi^{(2)}(z)$ must have a non-negligible Fourier component for the process [4,5], given by

$$\chi^{(2)}(\Delta k) = \int_0^L \chi^{(2)}(z)e^{i\Delta k}dz \quad (4)$$

Where L is the length of the nonlinear medium. Using this and considering the two waves with extraordinary polarization, we design a PPLN that follows

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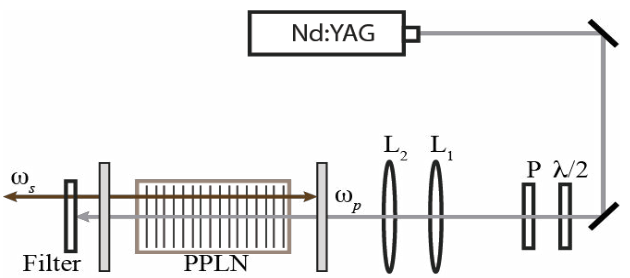
$$\chi^{(2)}(z) = \chi^{(2)}_{33}\,\mathrm{sgn}\left[\cos \Delta k\right] \quad (5)$$

Experimental Methods

We create a periodically poled lithium niobate crystal (PPLN) that has the appropriate Fourier component using standard photolithographic and electrical poling techniques [6] onto a 500 μm thick, z–cut $LiNbO_3$ wafer and the resulting crystal was placed in the experimental setup shown in Figure 1. As a pump we used aNd:YAG laser that emits 12 ns long (FWHM) pulses with a repetition rate of 10 Hz. We used a half-wave plate (λ/2) and a Glan–Thompson polarizer (P) to vary the energy of the pump beam. For increase the efficiency conversion the PPLN crystal was placed in a resonant cavity formed by two flat dielectric mirrors which are highly reflective (~90%) at the signal wavelength and highly transmitting (~99%) at the pump wavelength. The pump beam was focused to an elliptical cross-section (0.34 mm × 2.8 mm, FWHM) by using a pair of lenses, a 400 mm focal length spherical lens (L_1) and a 100 mm focal length cylindrical lens (L_2). A Filter at the output can be placed for allow pass only the wanted emission.

We do not have an IR spectrophotometer for analyze the spectral component of the output beam at this region however if we take out the filter placed at end of experimental setupa very weak red light is observed and their spectral component detected by a VIS spectrophotometer is centered at 709 nm wavelength (Figure 2). This red light is due to Sum Frequency Generation nonlinear process between pump and signal waves. Let ω_r the angular frequency of red light observed, by conservation of energy law for the SFG process we obtain that $\omega_r=\omega_s+\omega_p$ but $\omega_s=\omega_p/2$ then $\omega_r = \frac{3}{2}\omega_p$ and so we can deduce the wavelength of the signal wave being 2.1 μm. More details about red light observed are explained [5].

Using appropriate Filter, we block all unwanted spectral components and the energy of the 2.1 μm wavelength emission was measured. The output energy per pulse at 2.1 μm vs. pump energy is shown in Figure 3. The threshold is around 0.3 mJ and we are obtaining ~300 μJ of energy for the 2.1 μm wavelength when the crystal was pumped with 8 mJ of energy.



P: Glan-Thompson polarizer; λ/2: Half-wave plate; L_1: 400 mm focal length spherical lens, L_2: 100 mm focal length cylindrical lens.

Figure 1: Experimental setup for light conversion.

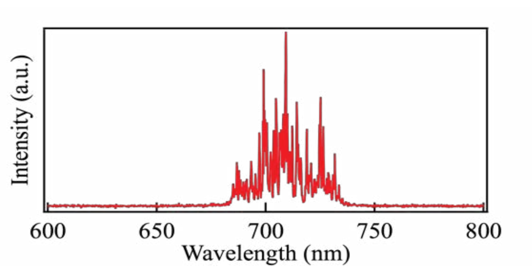


Figure 2: Spectrum of the output red light.

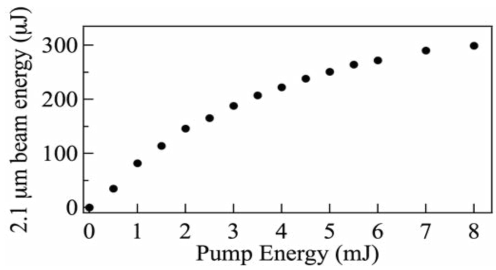


Figure 3: Output energy of the 2.1 μm beam vs. pump energy.

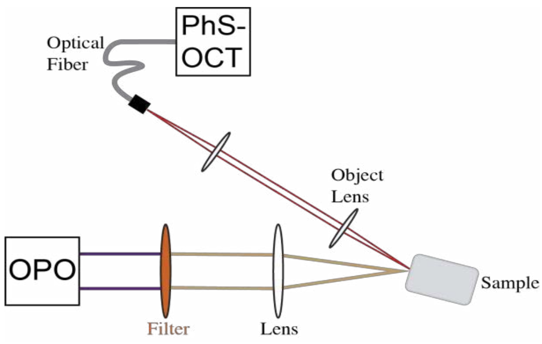


Figure 4: Experimental setup for shear wave generation.

By other hand, we use agar-agar powder to produce tissue-mimicking phantoms and we use the experimental setup shown in Figure 4 to verify if our output beam can be used for shear wave's generation instead a mechanical actuator. Agar is an easily accessible material that can be used to produce tissue phantoms with controllable mechanical properties like those of human soft tissue; a few drops of milk are added as scattering particles to facilitate OCT detection. We use the PhS-OCT system described [3] for our experiments but, of course replaced the mechanical actuator by the 2.1 μm wavelength emission focused on the sample by a spherical lens.

After several experiments, we observed that in fact we can produce shear waves in tissue phantom with the 2.1 μm emission. Figure 5 shows wave propagation pattern in agar phantoms detected by our PhS-OCT System when we pump with (a) 6 (b) 7 and (c) 8 mJ of energy, these results suggest that we need around 300 μJ of the 2.1 μm emission for produce shear waves inside tissue phantom. Of course, we can pump the tissue phantom with more energy for achieve better shear waves, however, due to limitations in our pumping laser used for this experiment we could not obtain more than 8 mJ of pumping energy.

Since the maximum pump energy that can be used is determined by the damage threshold of the PPLN crystal, which is approximately 3 J/cm^2, pumping the PPLN crystal with higher energy would not be a problem. Theoretically with the lenses arrangement indicated in Figure 1 we can pump the PPLN crystal up to ~33 mJ of energy.

Concluding Remarks

In conclusion, we made a simple, inexpensive device that emits nanosecond pulses of broadband 2.1 μm radiation, based on optical

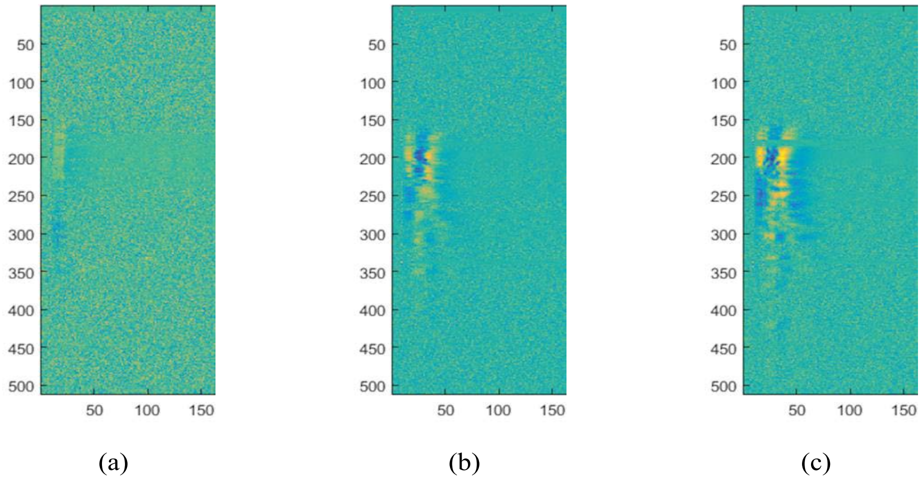


Figure 5: Wave propagation pattern inside tissue phantom for (a) 6 (b) 7 and (c) 8 mJ of pumping energy.

parametric oscillation at the degeneracy point in a periodically poled lithium niobate crystal. We obtained more than 300 µJ of radiation at 2.1 µm with 8 mJ of pump energy at 1.06 µm. The resulting emission can be used for shear wave generation in PhS-OCT technique for which we need at least 300 mJ of energy for shear wave generation.

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