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Investigation in acousto-optic laser stabilization for crystal resonator-based optoelectronic oscillators

Patrice Salzenstein
Centre National de la Recherche Scientifique
Institut Franche Comté Electronique Thermique
Optique Sciences et Technologie
Optics Department
Route de Gray, F25030 Besançon Cedex, France
E-mail: patrice.salzenstein@femto-st.fr

Vitaly B. Voloshinov
Arseniy S. Trushin
Lomonosov Moscow State University
Leninskie Gory
Moscow 119991, Russian Federation

Abstract. Potentialities are investigated for using acousto-optic cells based on a TeO_2 crystal to stabilize a microwave signal generated by an optoelectronic oscillator. Bulk acoustic waves at two radio frequencies (RF) near 60 MHz are launched in the two identical cells providing a required locking on of a microwave signal. Differences between RF signals are up to 400 kHz to follow quality factor of the optic resonator typically in the range of 5×10^8. Critical alignment of the two cells is performed thanks to an extraordinary polarized laser beam launched at a very low Bragg angle of light incidence. Moreover, the system is operating for any resonator to be inserted into the optoelectronic oscillator with a Q factor in the range of $2 \times 10^7 - 10^{11}$. [DOI: 10.1117/1.OE.52.2.024603]

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1 Introduction

In order to improve stability of an optoelectronic oscillator (OEO) based on an optical resonator,[1–7] it is necessary to stabilize optical frequency of the input laser at 1.55 μm. Although a Pound-Drever-Hall technique[8,9] can be used for the purpose, we investigate in this work the opportunity of using acousto-optic cells (AOC) based on a paratellurite TeO_2 crystal[10–12] to stabilize the microwave signal generated by the OEO. Although the acousto-optic modulator was already proposed for frequency stabilization of a diode laser system for atom trapping,[13] to our knowledge, it is the first time that it was proposed the use of AOC pairs for OEO stabilization. Bulk acoustic waves at two RFs near 60 MHz are launched in the two identical cells providing a required locking of the microwave signal. For an optical resonator with quality factor of the order $2 \times 10^7 - 10^{11}$, the difference between the two radio frequencies (RF) signals should be varied from 2 to 10 MHz, as it is explained in Sec. 4. In our case,[10,11] an extraordinary polarized laser beam on the cells ultrasound is sent at the Bragg angle of light incidence corresponding, at RF 60 MHz, to a deflector regime of the cells operation. It helped to perform a critical alignment of the two cells. To generate RF signals, a voltage controlled oscillator (VCO) is locked to a micro-controller following the microwave frequency generated by the OEO.

2 Operation of the Optoelectronic Oscillator

An OEO is generally an oscillator based on an optical delay line and delivering a microwave signal.[1] This delay line is equivalent to an optical resonator with a quality factor $Q = 2\pi FT$, where F is the microwave frequency, and T is the delay induced by the delay line.[3] The loop of the oscillator consists of an optic and an electric part, as schematically represented in Fig. 1. Light from the laser goes through a modulator driven by a signal from the detected light at its output, hence generating the oscillation. This light is then stored in the resonant element or delay line, and detected by a fast photodiode. The resulting microwave is then amplified and filtered. OEO can have optical output with the modulated optical signal and microwave output through a directional coupler. Instead of an optical delay line, an ultra-high Q whispering gallery-mode optical resonator allows a much more compact setup and easier temperature stabilization. To be introduced into the loop, the fabricated resonator has to be coupled to the optical light coming from a fiber. When OEO begins to work, some phenomena limit the ability to keep the resonance. In a previous publication, we reported difficulties in stabilizing the generated signal.[3] Thermal effects can certainly cause a drift of the frequency, so it is even possible to quickly loose the resonance after few minutes, making the measure of the phase noise too difficult. Therefore, it is necessary to stabilize the laser by locking it on the generated microwave frequency. AOCs are inserted to drive the laser frequency in order to improve its stability. It has to be underlined that an erbium doped fiber amplifier (EDFA) is needed to amplify the optical signal.

3 Main Principle of the Acousto-Optic Cell Operation

Our goal is to use an RF signal to generate acoustic waves in the crystals. The AOCs are to be inserted at output of the laser and in front of the modulator. Concretely, the incident light delivered by the laser is diffracted by the phase grating created in the cell by the acousto-optic effect. It diffracts and shifts the frequency of light using sound waves at radio-frequency. We are especially interested in one property. The light beam is scattered from the moving periodic planes of expansion and compression that change the index of refraction. Consequently, the frequency of the diffracted beam in a diffraction order m will be Doppler-shifted by an amount equal to the frequency of the sound wave F, which is an RF signal. The drift of the frequency of the light wave

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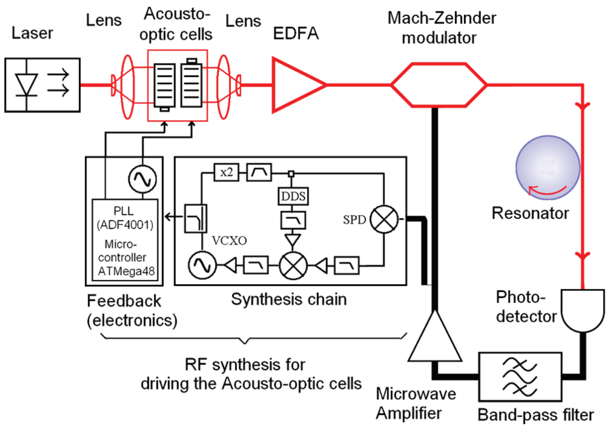

Fig. 1 Schematic representation of an optoelectronic oscillator (OEO) stabilized by acousto-optic cells. EDFA = erbium doped fiber amplifier; PLL = phase lock loop; DDS = direct digital synthesis; VCXO = voltage controlled crystal oscillator; SPD = sampling phase detector; RF = radio frequency.

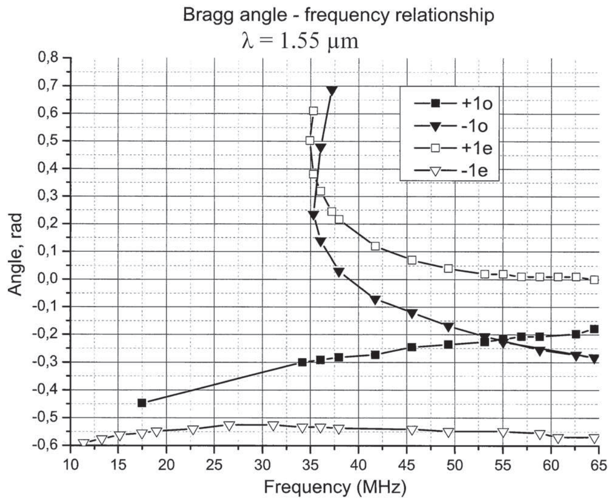

Fig. 2 Bragg angle (radian) versus RF frequency (MHz) for $\lambda = 1.55\ \mu$m for first order ordinary and extraordinary polarized modes $+1o$, $-1o$, $+1e$, and $-1e$.

$\upsilon = c/\lambda$ will be $\upsilon \rightarrow \upsilon + \mathrm{mF}$, where $m = \ldots -3, -2, -1, 0, 1, 2, 3\ldots$ is the order of diffraction. We must take into account that light will not only be shifted in terms of frequency, but also deflected at an angle θ depending on the wavelength of light λ relative to the wavelength of the sound Λ. The light beam emerges from the cell in form of a diffracted beam. The Bragg regime corresponds to a particular incidence angle where only one diffraction order is produced. In that case, the other diffraction orders are annihilated by destructive interference. The refractive indices of the incident and diffracted beams are different in an anisotropic medium because of a change in polarization direction associated with the interaction.

4 Installation of Acousto-Optic Cells in the Oscillator

4.1 *Alignment of AOCs*

As mentioned, AOCs are driven by RF signals. To shift the optic frequencies, we must choose the RF signal according to the quality factor of the resonator described in Sec. 2 of this manuscript. The wavelength of light is $\lambda = 1.55\ \mu$m. The velocity of light in the vacuum is $c \approx 3 \times 10^8$ m/s, so the frequency of light is $\upsilon = c/\lambda \approx 2 \times 10^{14}$ Hz. Considering a resonator with its $Q \approx 5.10^8$, we typically need to apply two RF signals to the cells in the range of $F_1 = 60$ MHz and $F_2 = F_1 + \Delta F$, where $\Delta F = \upsilon/Q = 400$ kHz. At this acoustic frequency, we need to apply only 6 V to each cell.

One difficulty is to select the good mode. If α is the angle of the incident beam arriving of the cell, we get:

$$n_0 = \sin \alpha / \sin \alpha_0 = 2.2597, \tag{1}$$

for the TeO_2 cell; $n_e = 2.4119$ at 630 nm.[14] For the wavelengths close to 1.55 μm, we find it interesting to select the first order extraordinary polarized mode ($+1e$ mode) because the Bragg angle versus RF frequency presents a floor at zero incidence angle for RFs between 55 and 65 MHz, as shown in Fig. 2.

The curves reported in this figure present the Bragg angle. They are obtained by measuring the deviation of the laser spot after going through an AOC. It has been determined for first order ordinary and extraordinary polarized modes $-1o$, $-1e$, $+1o$, and $+1e$ by applying RFs between 10 and 65 MHz.

The RF signals can then be shifted between 55 and 65 MHz. This 10 MHz maximal amplitude between the two RF signals allows us to work with a resonator with a Q-factor no worse than 2×10^7. If we can expect an ultra-high Q-factor in the range 10^{11} to be achieved and inserted in the OEO, it should require a 2 kHz difference between the two RF signals. So, the system is operating for any resonator inserted in the OEO while its Q-factor stays in the range $2 \times 10^7 - 10^{11}$.

Another difficulty is alignment of the two cells and their insertion between the laser and the modulator. The light is in the orange-red range at 630 nm, but it is not visible at 1.55 μm. Furthermore, the diameter of the beam delivered by the laser must be in the range of 1.0 to 1.5 mm. This value is larger than the 10-μm core diameter in the fiber. This fact impacts the dimension of the system: 30 to 50 mm are necessary in front and after the cells, and a typical distance of 50 mm separates the two cells. Even if the $+1e$ mode enables better alignment of the AOCs, the two cells are slightly misaligned and need to be rectified with a rotation stage. The optical frequency at output of the first cell after the first cell driven by F_1 RF signal is $\upsilon + F_1$, while the diffracted light propagates at a narrow angle relative to the incident beam. Similarly, after the second cell mounted at the output of the first cell, the frequency of light is $\upsilon + F_1 - F_2$, while the diffracted light at the output of two cells propagates along a direction only slightly different from the direction of the radiation incident on the first cell. So, it is easy to understand that alignment is relatively a critical step. The beam is then focused into an optical fiber at the input of the modulator.

4.2 *Locking AOCs*

Both RF signals set to the AOCs must be driven by a VCO because the frequencies need to be adjustable. We use a synthesizer to change both frequencies. Micro-controller Atmel "ATMega48" is used to control the synthesizer and also to measure the frequency if we do not use a phase lock loop (PLL). ADF4001 is a frequency synthesizer produced by Analog Devices. It consists of a low noise digital phase frequency detector (PFD), precision charge pump, programmable reference divider, and programmable 13-bit N counter. In addition, the 14-bit reference counter (R Counter) allows selectable reference frequencies at the PFD input. A complete PLL can be implemented if the synthesizer is used with an external loop filter and VCO or voltage controlled crystal oscillator (VCXO). To control ADF4001, we use a serial peripheral nterface (SPI). We need to have an access to a 24-bit register to set values of the N-counter and the R-counter.

4.3 *Estimating the Benefit on OEO Stabilization*

The RF is taken from the special clock output of the micro-controller. Stability of the frequency of our VCO is limited by the quartz stability. Yet it is enough for driving the AOCs. Indeed the best quartz oscillators are very stable.[15,16] Concretely, when operating with a frequency stability of 10^{-13} at 1 s at 60 MHz, in such a good case, it corresponds to -130 dBrad^2/Hz at 1 Hz from the carrier in terms of phase noise. The RF reference signal is driven by a synthesis chain described in Ref. 17. Thanks to this synthesis chain, the spectral density of phase noise $S_{\varphi S}$ can then be expressed in Eq. (2), by considering a time constant τ, which depends on the characteristics of the synthesis chain:

$$S\varphi_S = \left(\frac{4\pi^2 f^2 \tau^2}{1 + 4\pi^2 f^2 \tau^2}\right) \cdot S\varphi_0 + \left(\frac{1}{1 + 4\pi^2 f^2 \tau^2}\right) \cdot \frac{1}{n^2} \cdot (S\varphi_{\mathrm{ref}} + S\varphi_{\mathrm{DDS}} + S\varphi_{\mathrm{SPD}} + 4 \cdot S\varphi_{x2}), \tag{2}$$

where f is the Fourier frequency; τ is the integration time; and $S\varphi_0$, S_{ref}, S_{DDS}, S_{SPD}, and S_{x2} are spectral density of phase noise of the OEO, VCXO, direct digital synthesis (DDS) referenced to a 200 MHz signal coming from the VCXO frequency multiplied by 2, sampling phase detector (SPD), and the x2-multiplier, respectively.

The microwave signal of the OEO should be the main limiting contribution according to the best expected phase noise considered in microwaves for such a device: in case an OEO reaches the noise mentioned in Ref. 7, phase noise is still, respectively in the range of -110 and -160 dBc/Hz at 100 Hz and 10 kHz, respectively, from the 60 MHz signal. It is much more than the noise introduced by the synthesis chain which can be better than -135 and -165 dBc/Hz, respectively, at these Fourier frequencies. Thanks to the use of the synthesis chain to drive AOCs, the expected phase noise should not be degraded by the electronics.

5 Conclusions and Further Work

We have presented here a description of advantages and disadvantages of a pair of AOCs to stabilize a signal delivered by an OEO. Without any stabilization, we see that this signal is not sufficiently stable to allow phase noise measurement close to the carrier. The system operates in a proper manner only when the OEO is kept locked on the resonance. As result of this study, two RF signals in the range of 60 MHz presenting a difference no higher than 400 kHz were demonstrated to allow a significant better alignment of the two inserted AOC cells, thanks to the $+1e$ mode. We would like to underline the fact that the use of AOCs for locking an OEO is particularly interesting in the case of testing various resonators with different Q factors between 2×10^7 and 10^{11}. The RF to be applied on the cells just needs to be adjusted. Electronics is ready and will soon be useful for locking the loop and stabilizing the OEO with the cells. A further goal is to measure phase noise of the stabilized OEO at Fourier frequencies between 10 Hz and 100 kHz away from the carrier. To achieve our goal, we plan to use a dedicated optoelectronic phase noise measurement bench.[18–20] Although the phase noise measurements are not yet available experimentally, we expect the noise of the signal to be better matched with respect to the carrier.

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Patrice Salzenstein holds a master of research degree (Université des Sciences et Technologies de Lille – USTL, 1993), Graduate Engineering degree (Lille, Eudil, 1993), and PhD in electronics (USTL, 1996). From 1996 to 2001, he worked successively as a technology engineer (THOMSON–CSF Central Research Laboratory; now known as THALES–TRT), microwave engineer (ALCATEL–ALSTHOM Research Laboratory), and managed high frequency and time and frequency calibration laboratories ('Laboratoire central des industries électriques'). Since 2001, he worked at CNRS in FEMTO–ST Institute Besançon, France. He managed a calibration laboratory (phase noise and short term stability of frequency) between 2002 and early 2012. In 2010, his article was featured in *Electronics Letters* for his participation with Czech and Swiss colleagues to the best frequency stability ever measured on a quartz crystal oscillator: 2.5×10^{-14} at 5 MHz. Still working at CNRS, he is interested in research for optoelectronic oscillators and microwaves photonics applications.

Vitaly B. Voloshinov graduated from the Physics Department of Lomonosov Moscow State University (MSU) in 1971 with highest distinction and a student graduate award. From 1971 to 1973, he was a research engineer at Moscow Space Instrumentation Research Institute. In 1977, he got his PhD degree in radiophysics and quantum electronics in the Physics Department of MSU. Since 1976, he has been in the Physics Department of MSU. His scientific interests include acousto- and electro-optics, acousto-electronics, optical communication and optical information processing, spectroscopy, and laser technology. He has published about 380 scientific papers and been issued eight national patents. He has been a supervisor of many international and national scientific research projects and grants. He is an honorary professor at Lomonosov Moscow State University and the International Science Foundation.

Arseniy S. Trushin received his MS degree in 2002 from the Department of Physics of Lomonosov Moscow State University (MSU). He received his PhD degree in Lasers Physics in 2005 at Lomonosov MSU. From 2005 to 2009, he was at the Lebedev Physical Institute, Russian Academy of Sciences. Since 2009 he has been with the Department of Physics of Lomonosov MSU. His research interests include acousto-optics, physical acoustics, and luminescence. He is the author of more than a dozen of scientific papers published in Russia and abroad.