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Electrically driven thermal annealing set-up dedicated to high quality factor optical resonator fabrication

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Abstract

This paper reports on the development of an oven with a special purpose electronic board and specialist materials such as basalt fiber and nichrome. It is designed for optical resonators which are temperature controlled during their annealing process to increase their quality factor for the purpose of photonics applications.

Keywords: Optical resonator, Q-factor, annealing

1. Introduction

Progress in material and polishing techniques has enabled high quality factor optical resonators to be obtained for various optical and metrological applications. However, there is a need to improve quality factors of optical resonators (Q-factors). Ultra-high Q toroid micro-cavities and microrings have been performed on a chip [1], [2]. Research has recently shown high Q-factors for Whispering Gallery Mode (WGM) crystal resonators, such as calcium fluoride (CaF2) [3], magnesium fluoride (MgF2) [4], [5] and quartz [6] WGM resonators and spherical resonators [7], [8], [9], [10]. Different approaches in micro-sphere fabrication and various types of post-processing are presented in [8]. A resonator acts like a band-pass filter. Fundamentals and applications of WGM micro-resonators are given in [11]. Thermal annealing performed in the process of fabrication should increase the Q-factor [12]. This paper goes on to describe the fabrication process of an optical resonator, followed by a description of the electronics to control thermal ramp and allow a plateau to be reached. It then presents the developed oven and its efficiency.

2. Main steps in fabrication of a resonator

With reference to the results in [9] this section describes the fabrication process. The diameter is about 5 to 6 mm. The choice of diameter is dictated by the free spectral range in X-band. The first part of the process is the grinding. Grinding is necessary to achieve the right geometry for an optical guide. It consists of a 50 micrometer rim on the disk circumference. Silicon carbide must be used on a stable-deep-rooted support, because geometrical defaults must be downsized. Moreover, it increases the speed of grinding. Polishing is the second part of the process. This run is sufficiently efficient to reduce the roughness of the optical guide thanks to a sub micron powder in the diamond. The hardness of the disk considerably extends the time for each run and explains why the run must be slow. The improvement enables a 2 nm roughness to be produced, which sufficient to achieve a high Q-factor [10]. The Q-factor of the resonator is estimated through the cavity ring down spectroscopy method, as described in [12, 13]. It consists of quickly sweeping the probe wavelength across the resonance. During the last step of fabrication, thermal annealing ameliorates the aspects of resonator roughness and Q-factor [13], as it promotes crystal relaxation.

3. Electronics

The temperature of the resonator present in the inner part of the oven must be controlled to ensure regular increase. Resistance Temperature Detectors (RTD) and thermocouples (TC) have insufficient sensitivity for this purpose. The characteristics of sensors such as platinum resistance thermometers, thermistors and thermocouples can be found in [14]. A variety of techniques are provided in [15]. A thermistor is chosed to achieve this level of control, because its

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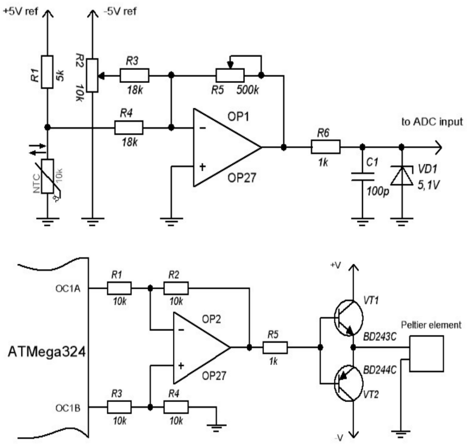
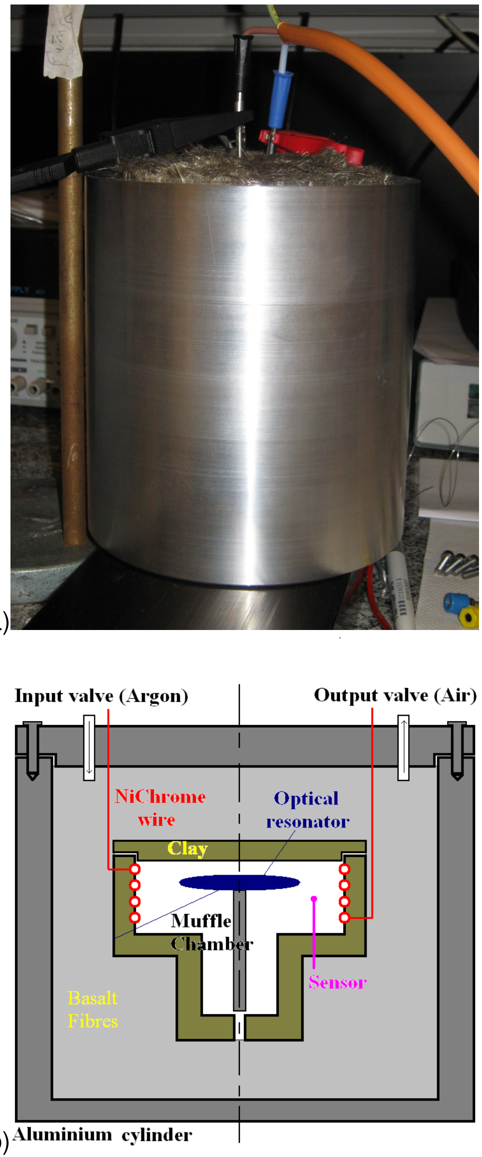


(a)

(b)

Figure 1: Input (a: upper side) and output (b: lower side) circuits. NTC means Negative Temperature Coefficient. ATMega324 is a micro-controller developed by the company Atmel. BD243C and BD244C are transistors. R1 to R4 are Resistances. OC1A and OC1B are dedicated pins. k and p are abbreviations for kOhm and pF. VD1 Zener diode on the right side of Fig. 1 (a) protects the micro-controller.



(a)

(b)

Figure 2: (a): view of the aluminum cylinder. (b): structure of the oven

reactivity is higher than TCs and RTDs. The micro-controller used is an ATMega324 [16, 17]. The characteristic curve of the thermistor must be linearized. That is why a shunt resistance is introduced on the board. Resistance is a decreasing function of temperature with respectively 12, 4.5 and 1 kOhm at 20, 60 and 100℃. According to this, in the program, the medium resistance is chosen relative to the average temperature. As seen on Fig. 1, Operational Amplifiers (OA) are the basic components for circuits and here one is mixed in parallel with resistances. This OA works like a shunt resistance and is an OP 27 precision low noisy OA, typically 3.5 nV/square root of Hz at 10 Hz. Its offset is low. It is compatible with high speed electronics. Offsets can be weak, e.g., only 25µV, and the local variation of temperature only changes it 0.6µV/K. Its 1/f noise has a corner frequency of only 2.7 Hz. Its high gain is typically 2xE6. These properties make it possible to carefully amplify very low level signals. For example, an 8 MHz bandwidth for gain and 2.8V/µs provide precise dynamic accuracy working in radio frequency when acquiring data. The electronics board is entirely renewed to reduce the contribution of the 1/f noise of the OAs.

4. Design and realization of a resonator dedicated oven

The aim of this particular oven is to provide a wide-ranging ability to test various processes for thermal annealing of optical resonators. The electronics detailed in the previous part enable the precise temperature driving of an optical resonator inserted in a special cavity while it is annealed. The oven operates at between 20 and 650 Celsius degres. The temperature and speed of the ramp must be high enough to relax the stress on the surface of the resonator, but low enough to avoid destruction of its surface. The oven must also be compact. A plan and picture of the oven are given in Fig. 2.

The cylindrical cavity is made of aluminum on the periphery. The muffle chamber is surrounded by basalt fiber [18] and inserted inside the oven. The basalt is chopped and its fibers have dry woven and non crimp fabrics. The fibers are milled to enhance heat insulating and fire blocking features. Wires are placed in a resistant alloy nichrome. The thermal conductivity of this alloy is 11.3 W/m/K. They are inserted inside a clay support. The shape of the support enables the resonators to be miniaturized for better thermal control. The principle of this annealing is to send a 1 to 6 A DC electric current inside the alloy. For illustration, Fig. 3 presents a resonator at the end of its process inside the muffle chamber.

Fig. 4(a) shows two similar attempts to achieve the desired maximum temperature at 600℃, to show the reproducibility of our oven. They consist in two 5.5A – 29V shots. Various speeds of thermal annealing are tested by increasing intensity in the nichrome wire. The step at 600℃ was successfully

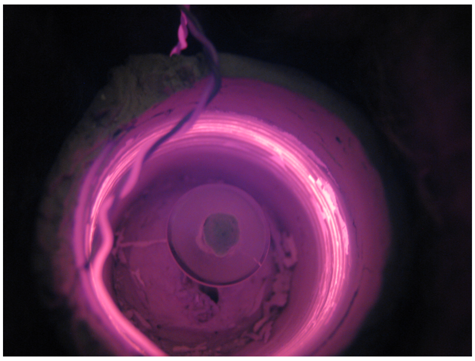


Figure 3: Muffle cylindrical compartment made from clay and inserted alloy. On the picture, a 5.5 A current is applied through the nichrome wire to heat an optical resonator. Its diameter is 5.5 mm

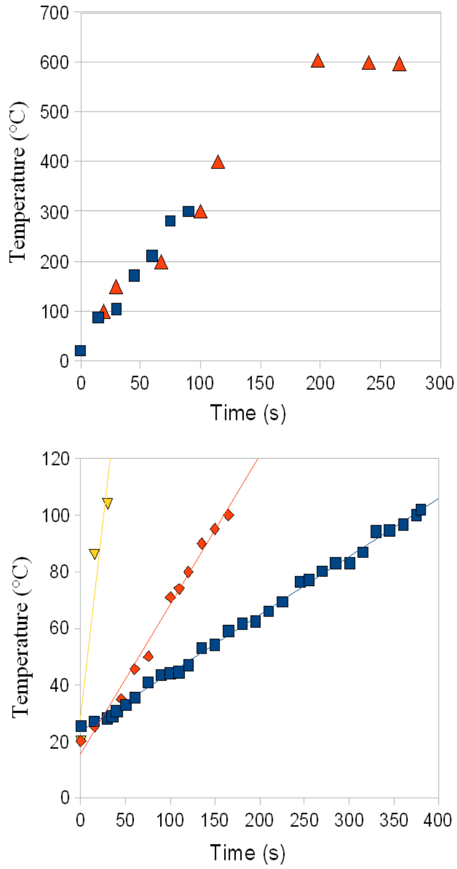


Figure 4: (a): Thermal annealing up to 600 ℃ (Square: 5.4A – 28.8V – Triangle: 5.5A – 29V). (b): Thermal annealing up to 100 ℃ (Square: 1.5A – 8.6V – Rhombus: 2.07A – 11.8V – Triangle: 5.4A – 28.8V

maintained after the initial ramp, represented by triangles on the corresponding figure. Moreover, the ramp of the annealing can be controlled by applying lower current. For illustration, Fig. 4(b) shows how 100 ℃ is reached for three electric currents and voltage, to check the linearity and the ability of our oven to deliver various speeds of thermal annealing. The designed and fabricated oven can achieve the objective of performing the desired ramp of annealing. Indeed, the optical resonator can then be protected from a possible thermal shock. Further tests show that the slow ramping process contributes to increasing the roughness, i.e., the Q-factor. The Q-factor determined by cavity ring down is given in [10], [13]. Finally, it contributes to boosting it in the range 1E9 [19–21] achieving the main goal of this work. It has to be underlined that this paper is the first to detail electrically driven thermal annealing contributing to these results.

5. Conclusion

By designing a new compact electronically driven oven, we show temperature control applied to an optical resonator component. The main benefit is to let the external surface of the component relax. Gain is achieved in terms of reaching roughness in the order of one nanometer. Notably, the main originality of our system consists of using a robust resistance wire and extremely fine fibers of basalt coupled with electronics based on a micro-controller.

Acknowledgments

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