Development of Original All-Optical Injection ControlCompetition and Gain Knock-Down Techniques for Laser Line Narrowing and Fixing at Atomic Absorption Line

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We describe two original and simplest, all optical techniques, to obtain a laser light, fixed at the frequency of a chosen reference atomic absorption line. The first type of systems is new development of our method [1,2] for laser spectral locking using a control by two frequency scanned, competitive injections with disturbed power ratio by the absorption at the reference line. We have developed a very simple method for eliminating of the typical laser locking limiting problem, concerning the locking in the presence of the normal fixed laser longitudinal mode structure. We have developed a laser system that combining the injecting control laser and laser amplifier using an original new technique for continuously tunable single mode laser operation in combination with synchronously and equal tuning of the modes of the amplifier. By adapting the laser differential rate equations, the system is analyzed theoretically in details and is shown its feasibility. The results correspond of previous our experiments. The second system is based of the laser amplifier arrangement with a gain knock-down from the competitive pulse, except at the wavelength of the desired absorption reference line. The theoretical modeling and the numerical investigations show the peculiarity and advantages of the system proposed. The developed laser system is of interest for applications as a frequency standard, in isotope separation system, in DIAL monitoring of the atmospheric pollutants and in spectroscopy. Also, the continuously tunable single mode laser (and the combination with the simultaneously tunable amplifier) resent itself the interest for many practical applications in spectroscopy, metrology, holography. We compare the action and the advantages of the two system proposed.

Keywords: laser, continuously tunable single mode laser, frequency locking, reference absorption line, external injection

1. Introduction

The lasers with fixed frequency of the emission at reference atomic absorption line (LFF) are of essential interest for spectroscopy applications, in isotope separation experiments, in atmospheric pollutants monitoring, and as frequency standards in optical communication systems. Two types of such devices are employed: i. that uses electro-mechanic comparative system [1], ii. based on physical phenomena that influence conveniently the laser generation [2-4]. First, used in practice, systems present very complex and expensive device. A development of a simple and chipper alternative device of the second type is an actual question in the literature [2-5].

Previously we have discussed the problem and have proposed a new way to obtain an efficient passive laser frequency locking introducing and applying the idea for bi-directional generation injection control in ring laser with disturbed by the absorption at the reference atomic line ratio of the two controlling injections

[3,4].The system contains an injecting frequency scanned laser and controlled ring laser. The method is simple for realization, energetically very effective and avoids non-desired influence of the external electric, magnetic and radiation fields. The volume with reference atoms can be placed at a long distance of the laser system that is of interest in the case of locking using as a reference substance the cooled atoms.

The main drawback of this promising method is the non-avoidable fixed and discrete mode structure of the controlled laser that limits the precision of the locking. This limitation is essential in the important case of locking at very narrow reference line that needs an injection from a single longitudinal mode laser. We present a further development of our method by introducing a new system for its realization, based of a new approach for continuous single-mode tuning of the injecting laser and for synchronous and equal tuning of the modes of the controlled laser. The new system solves the mode synchronization problem and thus increases essentially the precision of the locking. Also it is of interest as a simple and effective solution of the combination of continuously tunable single mode oscillator and laser amplifier.

The second development, reported also hiere, is related with proposition of a new amplifier gain knock down technique for all optical solution of the problem to produce laser light spectrally fixed at the atomic absorption line. The last technique is extremely simple for realization, free of the discussed mode hopping problems and the obtained line is naturally centered at the absorption maximum. However, due to the absence of the wavelength competition the linewidth of the locked line is large that this one obtainable by the counterinjection laser technique. In both cases the obtained line is narrow that the reference line. We have modeled the action of the system proposed and by the numerical investigtins we have shown their feasibility and advantages.

2. THE LASER SYSTEM WITHOUT MODE JUMPING. THE COMPLEX INVESTIGATION

The system is further development of the described in details by us earlier new method for laser frequency locking at atomic absorption line by disturbed bi-directional injection in a ring laser [3,4]. This method proposes many advantages, however like the other laser methods for such locking in standard applications its precision is limited by the problem of the existence of the mode-structure in the injecting laser and in the controlled laser. There are two problems: the first one is general and concerns the continuous tuning of the single-mode laser and the second one is the typical for the frequency locking system and concerns the fixed position of the locked laser modes that leads to the locking at a nod-defined parts of the reference line. This problem is very essential especially in the important case of precise narrow line locking at the reference line absorption maximum. The first problem is standard and continuously discussed in the literature [6]. The second problem is specific and of interest as for the case of the bidirectional injection locking as well as and for the development of the system continuously tuned single-mode oscillator - laser amplifier. The tuning of the slave ring laser is by frequency hopping at the fixed resonator modes. For the shown general case the line maximum not coincide with the resonator mode and thus the locking is in the wings of the line, the joined control of the tuning elements and resonator lengths. As it is evident such solution is very complicated, expensive and influenced by an external electro-magnetic disturbances. We have found a very simple and chipper new manner to produce a simultaneous and equal tuning of the frequency of the selecting line and the selected mode in the injecting laser and of the modes of the controlled ring laser.

In our proposal the injecting laser uses and main selector an Iinterference wedge 3 (3 -notation in Fig.1) [7,8,9] with a thickness e of 200 μm, wedge angle θ of 2.10^{-5} rad and reflectivity of the consisting mirrors of 0.9. The injecting laser resonator consists of the flat output mirror 6 (R=0.8) and the flat rear mirror 4 with the incorporated prism 2 (index of the refraction of the glass of 1.5) and as a pre-selective element second 3 μm thickness, wedge angle of 5.10^{-5} interference wedge 5 (reflectivity of the coatings of 0.8). The active medium 1 is a 10^{-3} mol/l Rh 6G dye in ethanol and the pumping for the all system is by 2 mJ, 50 ns, 0.53 μm harmonic from, 10 kHz repetition rate Nd:YAG laser (for active medium 1 – 1 mJ). In the prism 2 the resonator axis 7 is perpendicular to the axis OO' in which the prism 2 is translated parallel itself as it is shown with dashed thick line. This axis closes angles α (30°) and γ (15°) with the two side walls of the prism, AB and AC respectively. As we will show below, this angles can be chosen conveniently to assure simultaneous an equal change of the laser mode frequencies and the frequency of the mode selection, given by the wedge 3.

We use that during the translation of the prism 2 along the axis OO', the axis 7 suffers parallel translation (Δy) outside the prism, in the side of the smaller angle γ. In the other side of the prism, the direction of the resonator axis keeps its position. Thus the resonator of the injecting laser preserves its alignment during the translation. The parallel translation Δy leads to change of the point of incidence of the laser axis at interference wedge 3 and respectively to change with $\Delta \nu_{sl}$ the wedge resonant frequency of the transmission. From geometrical consideration we have:

$$\Delta y = \Delta x \cdot F_1(\alpha, \gamma, n),$$

where $F_1 = \left(\sin\gamma \cdot tg\,\gamma + \sin\alpha \cdot \sin(\beta_1 - \alpha) \cdot (\sin\beta_1 \cdot \cos\gamma)^{-1} - \sin\gamma \cdot tg\,\beta_2 \right) \cdot \cos\beta_2$

with $\beta_1 = \arcsin(n \cdot \sin\alpha)$, $\beta_2 = \arcsin(n \cdot \sin\gamma)$

This expression gives the possibility to choose in convenient manner the values of the noted parameters to assure continuously tunable single-mode operation. For the chosen angles a = 30° and y= 15° and x=1.5 and the given parameters of the interference wedges 3 and 5 that the needed relation for continuous and equal tuning of the modes in both cavities can be obtain. The range of the tuning is many GHz.

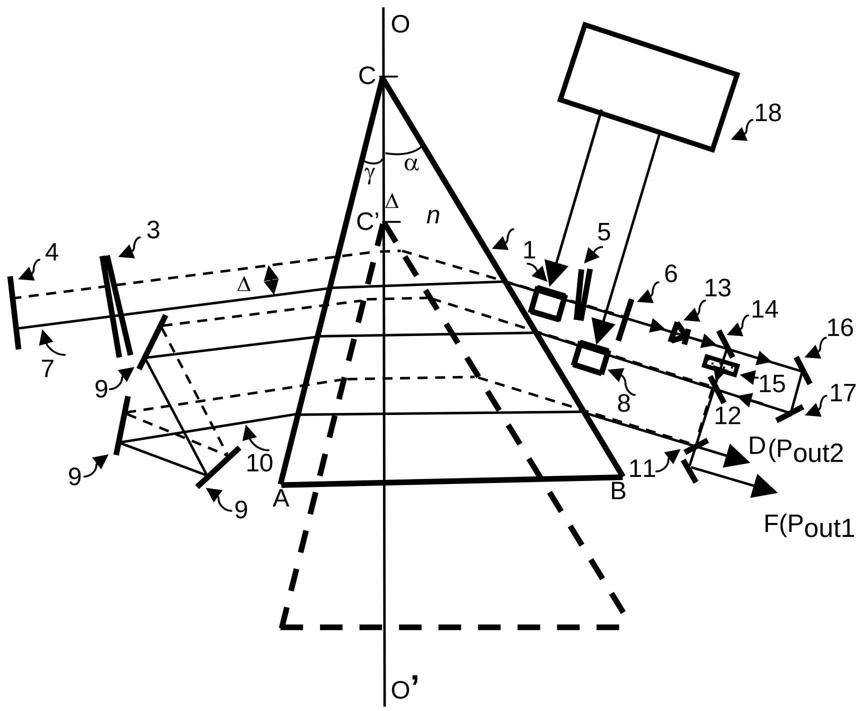


Fig.1. Diagram of the proposed new quantum electronics system. The notations are given in the text.

3. FREQUENCY LOCKING IN THE DESCRIBED SYSTEM

The system described can provide the continuously tunable single mode operation both for the injecting laser and the slave ring laser and the two generation are related by the injecting control. This avoids completely the problem of locking limitation by the resonator mode existence. The mode hopping during the tuning is avoided and real continuous frequency scanning by the ring laser generation of the absorption line is obtained. Due to the wavelength competition in the homogeneously broadened active medium [1,4], the narrowing of the locked line can be expected.

The laser action in condition of bi-directional injection ion this system is very similar as the considered earlier by us case of multimode injection [3,4] and can be also described correctly in a similar manner by the adapted rate differential equations [3,4,9], as it was made by us for multimode injection. We describe the system action by the following equations:

$$\frac{dN}{dt} = W_{P\ t.} \cdot N_t - \left(B_1 \cdot q_1 + B_2 \cdot q_2\right) \cdot N - \left[W_{P\ t.} + \frac{1}{\tau}\right] \cdot N$$

$$\frac{dq_1}{dt} = \left[B_1 \cdot V_a \cdot N - \frac{1}{\tau_{c_1}}\right] \cdot q_1 + \frac{k_1 N}{\tau} + \frac{P_{inj_1}}{h\nu_1}$$

$$\frac{dq_2}{dt} = \left[B_2 \cdot V_{a_2} \cdot N - \frac{1}{\tau_{c_2}}\right] \cdot q_2 + \frac{k_2 N}{\tau} + \frac{P_{inj_2}}{h\nu_2}$$

where *q;(t)* and *q₂(t)* are the generated photons number in the clockwise and counterclockwise directions respectively (the indices 1 and 2 will be related with clockwise and counterclockwise waves), *N* is the inversion population per unit volume in the active medium. N_t is the total number of the dye molecules per unit volume, which in our computation is equal to 6x10 cm" , *B\ =B₂ -<Jii2.li,2-C(/Va.L'i.2,* *<Y₂\(X)* - the emission cross-section (at the considered spectral region 1.85x10"^{16}cm^2); /₇ = l_2 is the length of the active medium 8andZ// = *L* 2 is the optical length of the ring resonator , V_a = 2.7xl0"^{4}cm^3 is the working volume of the active medium (here and below we give the typical experimental values); c_0 is the speed of light in vacuum, x = 3 ns and *m ci,c2 ⁼L'ria/co.yi,2* are respectively the lifetimes of the upper laser level and of photon in the ring cavity, where yi>2 describes losses in the cavity. The terms £Д/г give for /=1,2 the rates of photons produced in the laser mode volume by the spontaneous emission with k_t= 6x10"^{16} in our case. In the system *Wp(t)* is the pumping rate in the pulse that pumps AM (trapezium shape with 20/20/60 ns). The system is solved numerically by the Runge-Kuta-4 method. From the solution we obtain *qj(t)* and *q₂(t)* and respectively the laser output powers P_{out}j (Output F) and P_{out2} (Output D) [9]. In Fig.3 are plotted the calculated emitted powers (solid lines) where the injecting laser is continuously tuned forward-back by prism 2 translations and the absorption line (dashed line). During the scanning the Pinjl is modulated by the absorption T_a *(X)* at the reference line, given in Fig.3. The important feature of our methods is the narrowing of the emitted line by respect to the width of the absorption line. This narrowing is due to the well known wavelength competition effect in homogeneously broadened active medium.

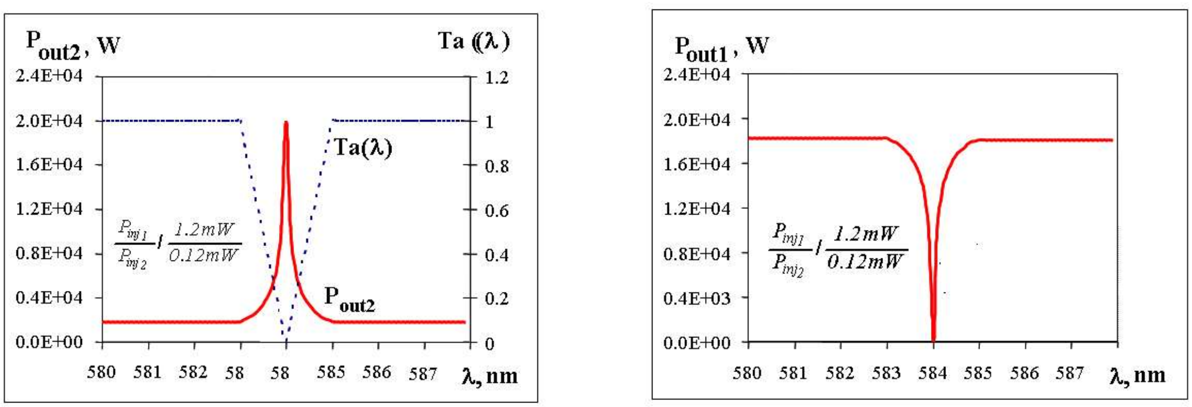


Fig2. Output powers from the ring resonator (P_{out1} – Output F and P_{out2} –Output D) obtained during the scanning of the injected wavelength – computed curves. The locking for Output D can be seen.

4. Gain Knock-Down Technique for Laser Frequency Locking at Atomic Absorption Line

Below we will discuss two schemes that realize our original approach for producing a passive locking at atomic line using the competitive amplification. It is convenient especially for single-frequency injecting laser and all resonances effects are avoided. In this case, a laser amplifier, working in saturation regime, is used. The idea of the approach exploits the possibility to amplifying in strongly competitive manner in the single amplifier two low-power pulses (IP_1 and IP_2 in the figures). The pulses are obtained from appropriate amplitude division of the output pulse IP from a repetitive, continuously tunable, single mode laser with a scanned wavelength [4]. The pulses form a sequence of pair of pulses (first sequence IP_1, IP_2). Intensity of the first sequence (IP_1), during the scanning, is modulated to approximately zero when its wavelength matches the absorption line maximum at the wavelengths λ_a by passing trough the absorption medium (see the figures). The intensity of each pulse IP_1 that

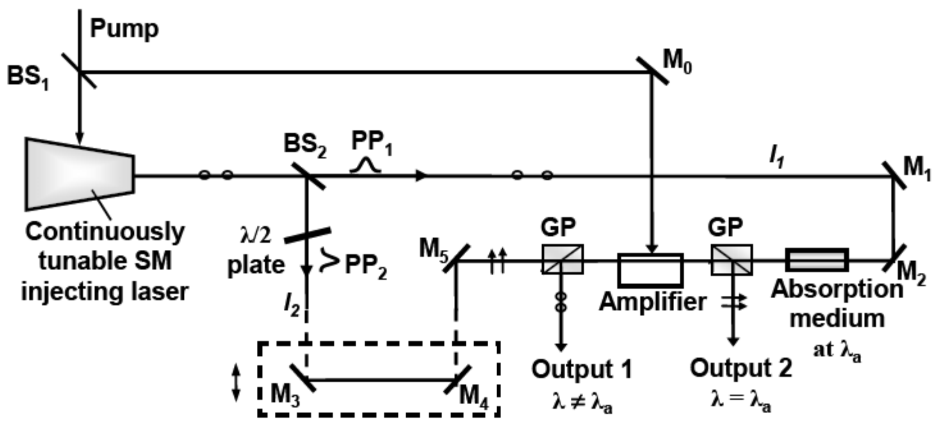
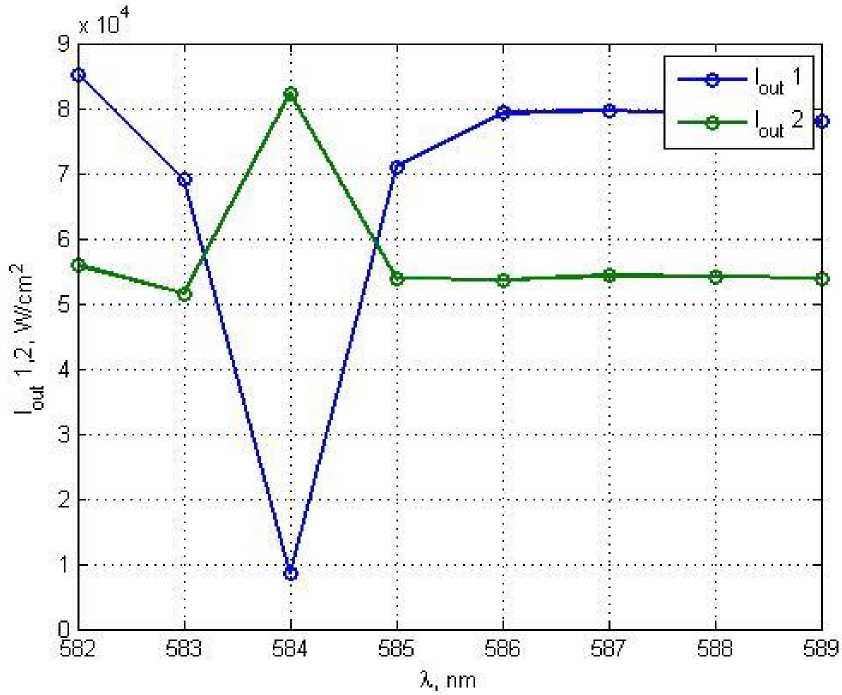


Fig.3. A schematic diagram of the set-up for gain knock-down laser frequency fixing

arrives in the absorption medium is higher in comparison with the corresponding pulse of the second sequence and arrives before it. Thus, this pulse depopulates the amplifier and prevents the amplification of the corresponding pulse of the second sequence. When the wavelength of the pulse IP_1 matches the absorption line, after passing the absorption medium, its intensity degrees to be very small to the populate the amplifier and the corresponding pulse of the second sequence is amplified. The output of the system that is taken from the direction of the propagation of the second sequence (Output 2), appears only at the wavelength at the absorption line λ_a. The realization presented in Fig.1, permits to overlap completely the directions of the two competitive pulse sequences in the amplifier and thus to obtain maximum competition. The dye solution with concentration of the Rh6G of 10^{-3} mol/1 in ethanol filled the cell with length of 1 cm. The pumping repetition rate is ~ 100 MHz and energy E_a in each pulse of ~ 10 μJ. The pumped volume V_a is accepted to be with diameter of 0.04 cm.

We have developed the modeling of the gain knock-down laser frequency fixing system that takes into account the Amplified Spontaneous Emission (ASE) presence during the inversion population creation and system operation.



E_{pump} = 0,005J

Fig.5. The calculated Output 1 (bottom curve) and Output 2 (top curve) for the input pulse wavelength scanning. The locking of the Output 2 at the absorption line and the exact coincidence of the locking line and of the absorption maximums can be seen.

The principle of development rely with division longitudinally of the amplifier of tens (or more) parts and summation of the emissions of all parts initially without the input pulse and with a given delay after the start of the pumping by taken into account the amplification of the input pulse. The detailed numerical analyses show the feasibility of this system. In Fig.4. are shown the calculated dependency of the two outputs of the system during the scanning of the frequency of the input pulses for amplification. It can be seen the strong increasing of the power of he Output 2 at the absorption line, spectral limitation of the emission inside the absorption linewidth and the coincidence of the maximum of the two lines – of the laser system output and of the absorption. The background emission can be eliminated by passing of the output 1 emission through the external nonlinear absorber.

5. CONCLUSION

Here, we have proposed two novel quantum-electronics system that permits to obtain a frequency locked laser emission at chosen reference atomic absorption line. The system is further development and improvement of our method for laser spectral locking using a control by two frequency scanned, competitive injections with disturbed power ratio by the absorption at the reference line. A shown here important feature of the system proposed is the very simple solution for eliminating of the laser locking limiting problem, concerning the locking in the presence of standard laser longitudinal mode structure. The last increasing the quality of the locking and enlarges the possibilities of the method to lock the laser at a very narrow absorption lines, comparable and less than the spectral distances between the locked laser resonator modes. The developed laser system is of interest for applications as a frequency standard, in isotope separation system, in DIAL monitoring of the atmospheric pollutants and in spectroscopy.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] Demtroder W., *Laser spectroscopy,* 2^n enlarged Edition, Springer, 1995

[2] Bezdin Ch., G.Brez, I. Golub, R.Shuker, *Laser self-frequency locking at atomic lines,* Optics Communications, 1984, Vol.48, pp. 357-361 and the literature therehin

[3] Deneva M., M.Nenchev, R.Barbe, J.-C-.Keller, *Unidirectional ring TLAI2O1 laser generation at the wavelength of an atomic absorption line by directional passive self-injection locking,* Appl.Phys.Lett, 2000, Vol.76, pp. 131-133 and the literature therehin

[4] Slavov D., M.Deneva, M.Nenchev, R.Barbe, J.-C. Keller, *Output control of a ring laser using bi-directional injection: a new approach for unidirectional generation at a reference atomic absorption line,* Optics Communications, 1998, Vol.157, pp. 343-351; 4a. M.Deneva ,M.Nenchev, Development of original Simple Quantum Electronics Devices with emission passively frequency locked at atomic absorption line. Proc. Intern. Confer. "Electrinics ET'2005", pp. 186-1193

[5] Endo, T., T.Yabasaki, M.Kitano, T.Sato and T.Ogawa, *Laser frequency locking at atomic line,* IEEE J.Quantum Electron, 1977, QE-13, pp. 955-961

[6] Nenchev M., Y.H.Meyer, *Continuous Scanning System for Single-Mode Wedge Dye Lasers,* Opt.Lett, Vol. 7, 1982, pp. 199-200

[7] Neveux M., M.Nenchev, J-C. Keller, R.Barbe, *A two-wavelength, passively self-injection locked, CWTi:*Al_20_3 *laser,* IEEE J.Quant.Electron., 1995, Vol.31, pp. 1253-1259

[8] Nenchev M., E.Stoykova, *Interference wedge properties relevant to laser applications: transmission and reflection of the restricted beams,* Opt.Quant.Electron.,Vol.25,1993, pp.789-799

[9] Deneva M., P. Uzuova , M.Nenchev, Tunable subnanosecond laser pulse generation using an active mirror concept, Opt.Quant.Electron.,Vol.39, 2007, pp.789-799