FM Spectroscopy of CPT Resonances with AOM Operating Purely in the Raman-Nath Diffraction Regime as Optic Phase Modulator

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Abstract - **We report on further development of a new method for frequency control of the external cavity diode laser with the use of FM sideband heterodyne technique where AOM operating purely in the Raman-Nath diffraction regime is employed as an external phase modulator. It is shown that the AOM design can be considerably simplified and its size can be minimized if the Raman-Nath diffraction regime is the dominant diffraction regime of AOM. We report on the production of the AOM - RN designed primarily for operation in such a regime with 2 mm acousto-optic interaction length.**

We have detected CPT resonances by means of FM spectroscopy with AOM-RN as an external phase modulator. In combination with reduced light shift, the capacity of extremely high-speed laser frequency tuning given by FM sideband technique can promise further improvement of short-term stability of frequency standards utilizing CPT clock transitions.

I. INTRODUCTION

It has been reported in [1] that, for the first time, phase-sensitive detection of the sub-Doppler resonances within D_2 absorption line of Cs atom has been carried out by means of conventional FM sideband heterodyne spectroscopy with acousto-optic modulator operating in the Raman-Nath diffraction mode as an external phase modulator. This technique has been used to obtain the error signals for wide bandwidth, high-speed servo-loop for frequency control of the external cavity diode laser (ECDL) as well [2].

It has been shown in [1,2,3] that the acousto-optic modulator (AOM) operating in the Raman-Nath diffraction mode as an external phase modulator has some features advantageous in comparison with EOMs which are conventionally used for the same purposes. All the results presented in [1, 2] have been obtained with the use of “ISOMET” model 1205-C2 AOM as an external phase modulator.

In [3] we reported on the AOM designed primarily for operation in the Raman - Nath diffraction mode and used as an external phase modulator in FM sideband heterodyne spectroscopy [4] for frequency control of the external cavity diode lasers. It has been shown that the AOM design can be considerably simplified and its size can be minimized if the Raman-Nath diffraction mode is the dominant diffraction mode of AOM.

In this paper, we report on the production of compact AOM-RN, acousto-optic modulator operating purely in the Raman - Nath diffraction regime with 2 mm of the acousto-optic interaction length.

We have analyzed both theoretically and experimentally the properties of AOM-RN. We have defined the dependence of the beat signal photo current and error signal amplitude on the acousto-optic interaction length. It is shown that FM spectroscopy with the use of AOM-RN is capable of measuring both the absorption and dispersion associated with spectral features.

We have detected coherent population trapping (CPT) resonances in saturated Cs vapor by means of FM spectroscopy with AOM-RN as an external phase modulator and have obtained error signals with amplitudes comparable with those of saturated absorption error signals.

II. THEORY

In this paper, we present the theoretical background of the AOM in the Raman-Nath diffraction regime in order to confirm its validity for use as phase modulator in the FM sideband heterodyne spectroscopy.

Let the sinusoidal elastic wave propagates through the homogeneous medium and a single-frequency laser beam is directed perpendicular to the wave vector of the elastic wave (Fig. 1). Acoustic wave running in the y direction induces periodical varying of the index of refraction compared with its initial mean value n_0 [5]:

$$n = n_0 + \Delta n \sin \Omega \left(t - \frac{y}{\upsilon} \right) \quad (1)$$

For light wave directed on x, the following expression is valid:

$$E = E_0 \cos \left(\omega t - \frac{2\pi}{\lambda_0} nx \right), \quad (2)$$

here λ_0 is a laser radiation wavelength in vacuum. Electric field of the light passed through acoustic beam of width L is given by

$$E_1 = E_0 \cos \left[\omega t + \Phi_0 + \Delta\Phi \sin \Omega \left(t - \frac{y}{\upsilon} \right) \right], \quad (3)$$

where $\Phi_0 = -(2\pi n / \lambda_0) L = -(2\pi / \lambda) L$ is a phase shift defined by mean value n_0 of the index of refraction and $\Delta\Phi = -(2\pi L / \lambda_0) \Delta n$ is a phase shift induced by varying part Δn of the index of refraction. Thus at any point on the acoustic wave edge ($x = L$, y = const), the light beam is phase modulated, and this modulation depends only on the time t. The electric field E_1 of the optical radiation passed through AOM will be described as

$$\begin{aligned} E_1 &= E_0 J_0(\Delta\Phi)\cos(\omega t + \Phi_0) + \\ &+ E_0 \sum_{N=1}^{\infty} J_N(\Delta\Phi) \times \\ &\times \left[\cos(\omega t + N\Omega\tau + \Phi_0) + (-1)^N \cos(\omega t - N\Omega\tau + \Phi_0)\right] \end{aligned} \quad (4)$$

here $\tau = t - y/\upsilon$.

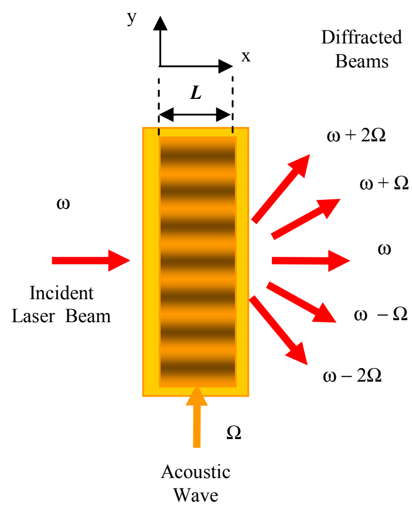

Fig. 1. Geometry of interaction of the light with the acoustic wave.

Thus light wave spectrum has a maximum at carrier frequency ω and sidebands at $\omega \pm N\Omega$, since $\tau = t - y/\upsilon$, where N is integer number. The amplitude dependence of the carrier and of the sidebands on the phase shift $\Delta\Phi$ is given by Bessel functions $J_N(\Delta\Phi)$.

At any moment the carrier phase angle $\Phi_0 = -(2\pi n/\lambda_0)L$ does not depend on y. This is not valid for the waves corresponding to the sidebands. The interference of the waves of the same order irradiated from the acoustic beam rear edge ($x = L$), leads to their addition only in case when they are directed at some angle ϑ_N. Sidebands of the order N at frequency $\omega + N\Omega$ are reflected at angle ϑ_N, and the sidebands at frequency $\omega - N\Omega$ experience symmetrical reflections. Thus the input light beam, directed perpendicular to the acoustic wave direction, splits in a row of the beams diverging at the angles ϑ_N symmetrically relative to the incidence direction of the light. These angles are defined by : $\sin\vartheta_N = \pm N(\lambda/\Lambda)$.

Dropping out in (4) the terms describing constant phase shift, we get the expression

$$\begin{aligned} E_1 &= E_0\cos(\omega t + \Delta\Phi\sin\Omega t) = \\ &= E_0 J_0(\Delta\Phi)\cos(\omega t) + \\ &+ E_0\sum_{N=1}^{\infty} J_N(\Delta\Phi)\left[\cos(\omega + N\Omega)t + (-1)^N\cos(\omega - N\Omega)t\right] \end{aligned} \quad (5)$$

So, the AOM output radiation has a pure FM spectrum. The phase modulation $\Delta\Phi = -(2\pi L/\lambda_0)\Delta n$ plays the role of the modulation index M. The amplitude of modulation of the index of refraction equals, according to [6], to

$$|\Delta n| = (n_0^3\, p/2)\sqrt{2I/\rho\upsilon^3}\,, \quad (6)$$

where $I = P/Ld$ is sound wave intensity, ρ is the volume density of the crystal material, p is a photo-elastic constant, d is a width of the acousto-optic interaction area or light beam diameter. The index of refraction varying is proportional to the square root of acoustic power and is inversely proportional to the square root of the acousto-optic interaction length. Thus light wave phase modulation will be proportional to the square root of the acousto-optic interaction length:

$$\Delta\Phi = -(2\pi L/\lambda_0)\,\Delta n \sim (L)^{1/2}. \quad (7)$$

For example, in case of crystal TeO_2 with the following values of

$n = 2.367$, $\upsilon = 4.2$ km/s, $\lambda_0 = 850$ nm, $P = 40$ mW, $\rho = 6.0\cdot10^3$ kg/m^3, $p = 0.24$, $d = 2$ mm,

$\Delta\Phi$ value equals to $\Delta\Phi = -(2\pi L/\lambda_0)\Delta n = -0.16$ for $L =$ 2mm.

We have reason to assume that $|\Delta\Phi| \ll 1$, therefore $J_0(\Delta\Phi) \cong 1$, $J_{\pm1}(\Delta\Phi) = \pm\Delta\Phi/2$, and the terms of higher order vanish and (5) simplifies to

$$E_1 = E_0\cos(\omega t) + E_0(\Delta\Phi/2)\times \\ \times\left[\cos(\omega + \Omega)t - \cos(\omega - \Omega)t\right] \quad (8)$$

Thus the spectrum of the optical radiaton passed through AOM operating in the Raman-Nath diffraction mode will consist of the strong carrier at frequency ω and of two weak sidebands at $\omega \pm \Omega$ and with amplitudes $|E_0(\Delta\Phi/2)|$ diverging at the angle ϑ_1 symmetrically relative to the incidence direction of the input light. The ratio of powers of each sideband of ±1st diffraction order to the carrier power is $P_{\pm1}/P_0 = (\Delta\Phi/2)^2$.

In our experiments, the dispersive medium of length l is a cesium saturated vapor cell. The saturated absorption resonances of D_2 line of Cs atom were probed in the field of two counter-running radiations. One of them, saturating the absorption, had the carrier frequency ω, and the second one, probing the transition, consisted of three beams corresponding to the carrier and to the sidebands of ±1st diffraction order at frequencies $\omega \pm \Omega$.

Following the theory of FM spectroscopy, described in detail in [4], and introducing amplitude attenuation δ_N and phase shift ϕ_N, experienced by each frequency component, we will find the expression for the intensity of the light $I_2(t)$ incident on a photo detector :

$$I_2(t) = c|E_2|^2/8\pi = \frac{cE_0^2}{8\pi}e^{-2\bar{\delta}}\times \\ \times\left[1 + \Delta\delta\,\Delta\Phi\,\cos\Omega t + \Delta\phi\,\Delta\Phi\,\sin\Omega t\right] \quad (9)$$

where $\Delta\delta = \delta_1 - \bar{\delta}$, $\Delta\phi = \phi_1 - \bar{\phi}$ are the values describing the deviations from the background values caused by the optical transition. Thus the $\cos\Omega t$ and $\sin\Omega t$ components of the beat signal are directly proportional to the absorption and dispersion, respectively, and the beat signal photocurrent will be proportional to $\Delta\Phi$ and, as followed from (7), to $(L)^{1/2}$.

III. EXPERIMENT

The experimental set-up is shown in Fig. 2. Grating stabilized diode laser in the Littrow configuration provided tunable single-frequency input radiation at 851nm.

The AOM-RN single pass output presenting pure frequency modulated and spatially separated optical spectrum was used as a probe beam for saturated absorption spectroscopy in a magnetically shielded cesium vapor cell at room temperature and was focused

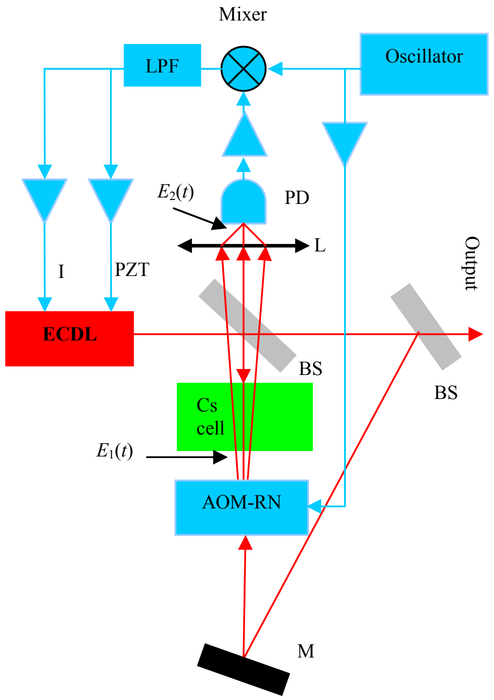

Fig. 2. Experimental set-up. ECDL – external cavity diode laser; PZT – piezoelectric transducer; BS – beam splitter; M – mirror; AOM – acousto-optic modulator; L – lens; PD – photo detector; I – injection current; DBM – double-balanced mixer.

on a p-i-n photo-detector. The ratio of powers of each ±1st diffraction order sidebands to the carrier power in front of the input window of the Cs cell was typically about 5%.

The rf beat was detected by the heterodyne detection using double-balanced mixer, which produced dc signal, obtained when the laser frequency is scanned across Doppler profile of cesium D_2 absorption line and coincides with the optical transition frequencies $6S_{1/2}$, F = 4 – $6P_{3/2}$, F' = 3, 4, 5, where F F' are the total angular momenta of the atom in the ground and excited states.

These signals served as the error signals for our ECDL servo system. Tuning the saturating beam to resonate with the same atom as the probe carrier leads to zero dispersive effect. When the saturating beam is in resonance with the atom resonant with either sideband, two resonances are obtained with $2(\Omega/2) = \Omega$ separation. This situation is illustrated in Fig. 3.

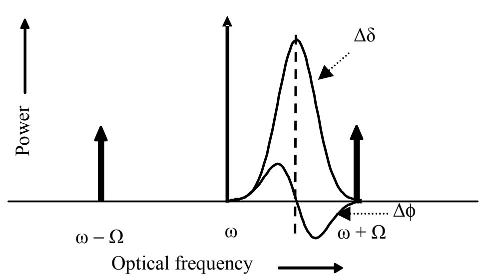

Fig. 3. Frequency-domain illustration of FM spectroscopy employing AOM in Raman-Nath diffraction regime.

According to [7], the limit conditions on Raman-Nath diffraction or on the Bragg deflection regimes are defined by the dimensionless Klein-Cook factor: $Q=2\pi L\lambda/\Lambda^2$, where L is the acousto-optic interaction length, λ and Λ are the light and the acoustic wavelengths, respectively. The area Q< 0.3 corresponds to the Raman-Nath case, and the Bragg diffraction mode is dominant at Q>4π.

Developed at VNIIFTRI and designed for operation in pure Raman-Nath diffraction mode, AOM-RN with 35 MHz center frequency and with 20 MHz sweep bandwidth has Q=0.41 and Q=0.1 at 40 MHz and 20 MHz modulation frequency, respectively. Its acousto-optic crystal material is TeO_2. The 2 mm acousto-optic interaction length is about one order smaller than that of 1205-C2 AOM. At such Q value, Raman-Nath diffraction mode is dominant, and Bragg deflection of the light mainly into one beam of the first diffraction order is not visually observed yet, even when the incidence angle is comparable with Bragg incidence angle value. At 40 mW of the driving AOM rf power, the zero background level of the error signals was achievable for all of the sub-Doppler resonances without noticeable losses in the amplitude of the signals compared with those obtained when 1205-C2 AOM was used.

Since the ratio $P_{\pm 1}$ / P_0, sufficient to conduct FM spectroscopy, appeared so small, we have removed the impedance matching circuit. The same 40 mW of rf power of the local oscillator fed the piezoelectric transducer directly through rf cable. Figure 4 represents, for comparison, the photographs of “ISOMET” 1205-C2 AOM and pair of “VNIIFTRI” AOM-RN.

Thus the shortening of the acousto-optic crystal allowed to minimize considerably the size of AOM designed for operation in pure the Raman-Nath diffraction mode.

To establish the correspondence with FM spectroscopy theory [4], we have analyzed the error signal line shape in the saturated absorption spectroscopy experimental configuration illustrated in frequency domain in fig. 3. Since the line shape and line width can vary due to the power broadening, we varied laser beam intensity before its entering AOM-RN. At different but fixed modulation frequency values, for two different saturating $I_{1,2}$ field intensity values, we scanned carrier frequency through chosen single saturation absorption resonance.

Curves 2 in fig. 5 and fig. 6 show experimental error signals corresponding to the absorption and dispersion components defined in (9). The signal corresponding to the dispersion shows three overlapping dispersion curves, which occur due to the successive resonant interaction of all three components of the probe field. The signal corresponding to the absorption clearly shows a negative-going signal, which reproduces the absorption line shape probed by the upper sideband, followed at a spacing $2(\Omega/2)$ by a positive-going signal, which reproduces the same absorption line shape probed by the lower FM sideband. Thus FM spectroscopy with AOM-RN as an external phase modulator is capable of detecting both the absorption and dispersion features of the investigated optical resonances.

Fig. 4. Photographs of the "ISOMET" 1205-C2 AOM and of the "VNIIFTRI" AOM - RN.

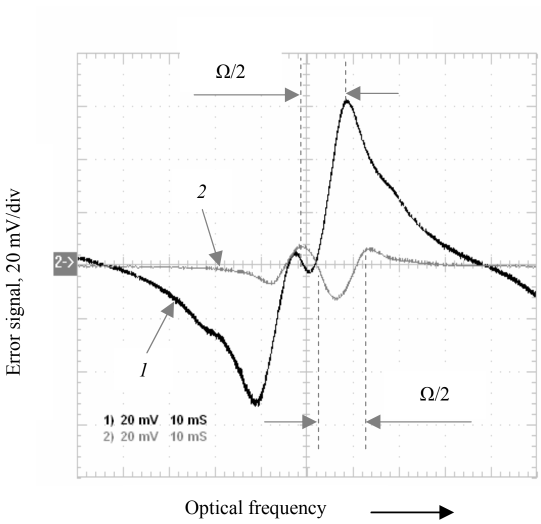

Fig. 5. Error signal corresponding to the dispersion. Intensity ratio I_1/I_2=4. Ω=26,02 MHz. The horizontal axis scale is the same for curves *1* and *2*.

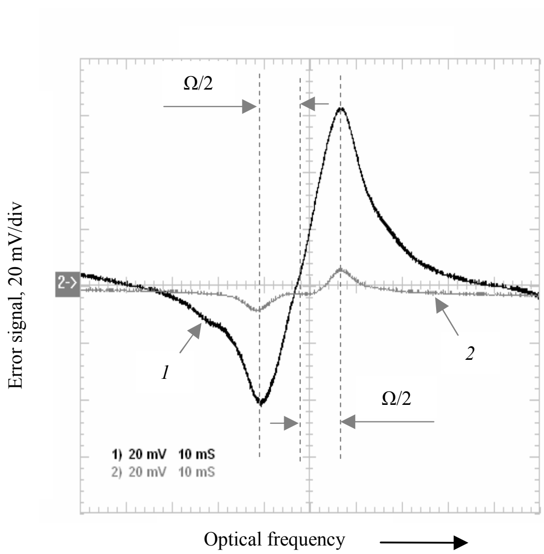

Fig. 6. Error signal corresponding to the absorption. Intensity ratio I_1/I_2=4. Ω=25.76 MHz. The horizontal axis scale is the same for curves *1* and *2*.

We have analyzed the capacity of FM spectroscopy with AOM-RN phase modulator for detecting narrow CPT resonances [8] in saturated cesium vapor. Since at resonant interaction with bi-chromatic laser light, the atom is in the non-absorbing state, the ac Stark shift should be of reduced value compared with that when the atom is in absorbing resonant state. In combination with reduced light shift, the capacity of extremely high-speed laser frequency tuning given by FM sideband technique can promise further improvement of short-term stability of frequency standards utilizing CPT clock transitions.

Fig. 7 shows experimental set-up used for detection CPT resonances in Cs saturated vapor at room

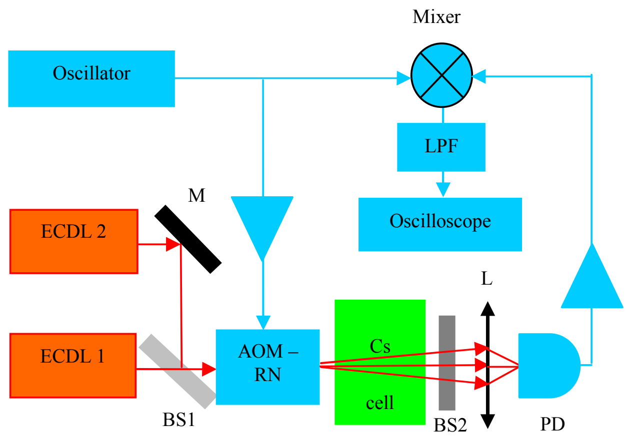

Fig. 7. Experimental set-up for detection CPT resonances. ECDL – external cavity diode laser; BS – beam splitter; M – mirror; L – lens; PD – photo-detector; LPF – low-pass filter.

Two collinear light waves of the same linear polarization from two independent ECDL1 and ECDL2 couple both $6S_{1/2}$, F=3; F=4 ground state hyperfine levels to a common hyperfine level of the $6P_{3/2}$ excited state. The frequency of ECDL2 was tuned close to $S_{1/2}$, F=3 ↔ $P_{3/2}$, F'=4 transition, while ECDL1 was scanned across $6S_{1/2}$(F=4) – $6P_{3/2}$ (F'=3,4,5) manifold. A curve *1* in fig. 8 is the error signal in saturated absorption experimental set-up when the beam splitter BS2 provided the saturating counter beam, while ECDL2 radiation was blocked before entering AOM-RN and did not come onto photo detector. The curves *2* in fig. 8 and *1* in fig. 9 are the same error signals as curve *1* in fig. 8 at absence of saturating radiation, when BS2 has been removed from the optical table. In this case, the experimental configuration corresponds to that described in [4]. When ECDL2 radiation is unblocked, radiations from both lasers are present in the cesium cell and come onto photo detector. The curves *2* in fig. 9 shows clearly three successive dispersion like error signals separated in frequency by Ω and formed in turn by the upper sideband, by the carrier and by the lower sideband. These three error signals correspond to the CPT resonances arising at the moment of coincidence of ECDL1 and ECDL2 frequency difference value with ground state hyperfine levels frequency separation value. Thus we

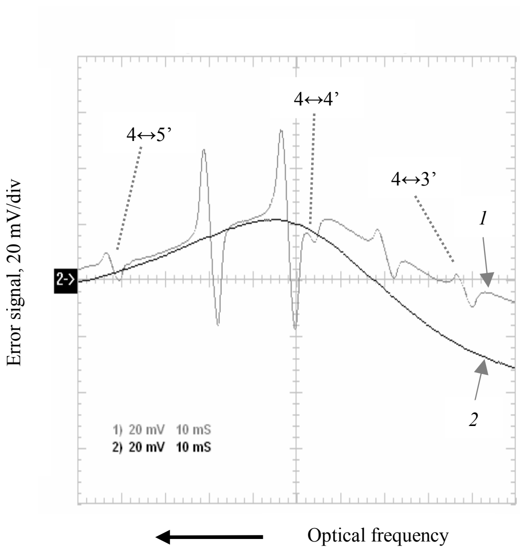

Fig. 8. A curve *1* is the error signal, when the beam splitter BS2 provided the saturating counter beam, while ECDL2 radiation was blocked before entering AOM-RN and did not come onto photo detector. The curve *2* is the same error signal at absence of saturating radiation, when BS2 has been removed from the optical table.

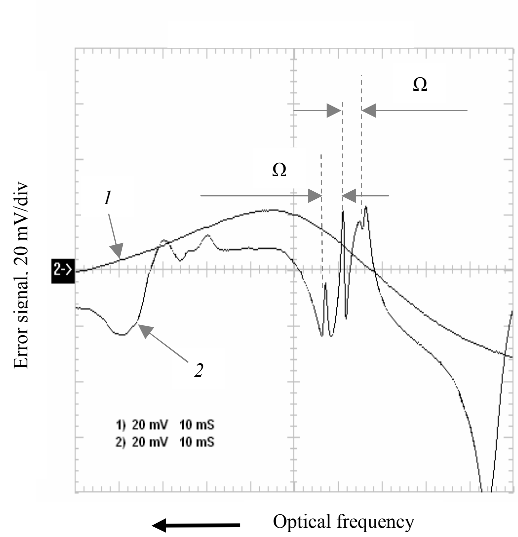

Fig. 9. A curve *1* is the same error signal as *2* in fig. 8. The curve *2* is the same error signal when ECDL2 radiation was unblocked.

have demonstrated that the detection of CPT resonances by means of FM spectroscopy with AOM-RN as external phase modulator is possible.

IV. CONCLUSION

We presented the theoretical and experimental analysis of AOM designed for operation in pure Raman - Nath diffraction mode and used as an external phase modulator in FM sideband heterodyne spectroscopy for frequency control of the ECDL.

The amplitude dependence of AOM output spectrum on the acousto-optic interaction length has been defined.

We reported on the production of AOM-RN with 2 mm acousto-optic interaction length and designed primarily for operation in pure Raman-Nath diffraction mode. Such compact devices can be used as phase modulators in a wide range of applications in laser spectroscopy, where the frequency noise reduction of a variety of the lasers is essential.

It is shown that FM spectroscopy with AOM-RN as an external phase modulator is capable of detecting both the absorption and dispersion features of the investigated optical resonances.

We have demonstrated that the detection of CPT resonances by means of FM spectroscopy with AOM-RN as external phase modulator is possible. In combination with reduced light shift, the capacity of extremely high-speed laser frequency tuning given by FM sideband technique can promise further improvement of short-term stability of frequency standards utilizing CPT clock transitions.

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