TIME AND ENERGY CHARACTERISTICS OF AN ATOMIC RESONANCE FLUORESCENCE FILTER

A.V. Belinskii, M.G. Dubenskaya, and A.A. Podshivalov

M.V. Lomonosov State University, Moscow

Received May 15, 1991

Based on an earlier developed technique a computer simulation of the atomic resonance fluorescence has been done that allowed us to calculate the stretching of a pulse response and the conversion coefficient of a cesium atomic vapor fluorescence filter.

Analysis of specifications of the laser communication channels (LCC) in which optical signals propagate through weakly absorbing scattering media and are detected under conditions of natural optical noise, shows that the reliability of the data transfer through the LCC can be improved mainly by narrowing the spectral sensitivity range of a photodetector (PD) (at best, it should be close to the value at which the noise component of photocurrent induced by the remaining optical illumination becomes equal to the level of intrinsic noise of the PD) and corresponding narrowing of the spectrum of radiation from the optical transmitter.

Existing methods of controlling the spectrum width of laser radiation enable one to generate the tunable optical pulses with the optical spectral width less than 0.001 nm.[1] At the same time, the spectral region of the most sensitive photodetectors, i.e., PMT's is much wider (~ 300 nm).

For narrowing the spectral sensitivity range of a PD, an optical filter is installed in front of a PMT that, in the case of the PD used in the LCC, must be: (1) narrow–band, (2) with wide field of view, and (3) must not introduce additional noise.

Optical filters in which the narrow–band absorption resonances in atomic gases[2] are exploited can most fully meet these requirements. These filters have the characteristic pass band of 0.001 nm, high uniformity of the optical characteristics over the filter aperture, and guaranteed stability of the position of central transmission frequency (not less than 5×10^5).

One of the most promising devices of such a type is the cesium atomic resonance fluorescence filter (ARFF)[2] which has two isolated transmission lines at 455.5 and 459.3 nm with spectral bandwidth ~ 0.0005 nm. This instrument is characterized by wide field of view and low residual transmission (at frequencies off the transmission band). The construction of the ARFF is illustrated in Fig. 1*a*. It consists of the transparent cell filled with gaseous cesium in the atmosphere of a buffer gas that is placed between two glass filters *1* and *3*. Signal radiation at the wavelength 455.5 or 459.3 nm passing through the input blue filter *1* is absorbed by cesium atoms. The excited atoms relax into the ground state emitting fluorescent radiation at the wavelengths 852 and 894 nm that passes through the red output filter *3* and is detected by the photomultiplier *4*. The wide field of view of the ARFF is provided by the isotropy of absorption by atomic vapors, while low off–resonance transmission results from the fact that the transmission bands of filters *1* and *3* do not overlap and the resulting filter is nontransparent for radiation at other wavelengths. The main factor that needs to be accounted for in the analysis of operation of the ARFF is the effect of radiation capture due to multiple isotropic reemission by the atoms of resonance IR fluorescence which leads to stretching of the recorded pulse and to a decrease of a fraction of the signal to be detected in the total signal.

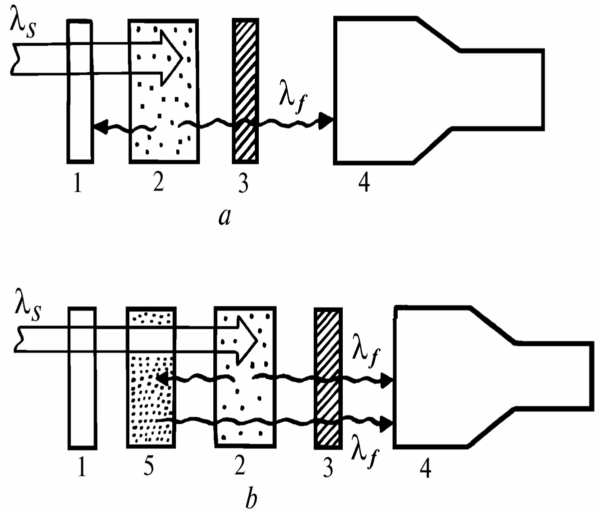

FIG. 1. The construction of the atomic resonance fluorescence filter: 1) filter transparent at the wavelength of signal radiation, 2) converting cell with pure vapor or with the cesium vapor in the atmosphere of a buffer gas, 3) filter transparent at the wavelength of the atomic fluorescence, 4) photodetector, and 5) reflecting cell with the cesium vapor in the atmosphere of a buffer gas.

In this paper based on the theory developed previously the numerical simulation of the processes occurring in the cell with cesium vapor due to multiple reemission of resonance fluorescence was performed that allowed us to calculate stretching of a pulse response of the ARFF and the coefficient of conversion into IR radiation (filter conversion coefficient). Analogous calculations were made for the case of a two–sections ARFF which has demonstrated the possibility of increasing considerably the conversion coefficient.

Theoretical consideration of the processes of resonance absorption and fluorescence will be conducted for the case of an infinite in the transverse directions cell with the thickness L and filled with cesium atomic vapor. When the signal radiation at the wavelength coinciding with that of cesium absorption resonances at 455.5 nm (459.3) and with duration shorter than the lifetime T_1 of this resonance is incident on the cell, the instantaneous distribution of excited atoms over the cell depth is

0235-6880/92/11 230-04 $02.00

$$F_0(z, \nu) = F_0(z = 0, \nu) \exp(- K_s z) , \tag{1}$$

where K_s is the absorption coefficient at the frequency ν of signal that can be varied in the range $K_s \simeq (1 - 10)$ cm^{-1} by varying the vapor density and pressure of a buffer gas. The specific feature of cesium is that the absorption coefficient K_f at the fluorescence wavelengths (852 and 894 nm) exceeds the absorption coefficient of signal radiation by two orders of magnitude: $K_f \simeq (70\text{–}300) K_s$. As a result, the radiation from the atomic fluorescence undergoes multiple absorption and isotropic reemission before it reaches the cell boundary and escapes the cell.

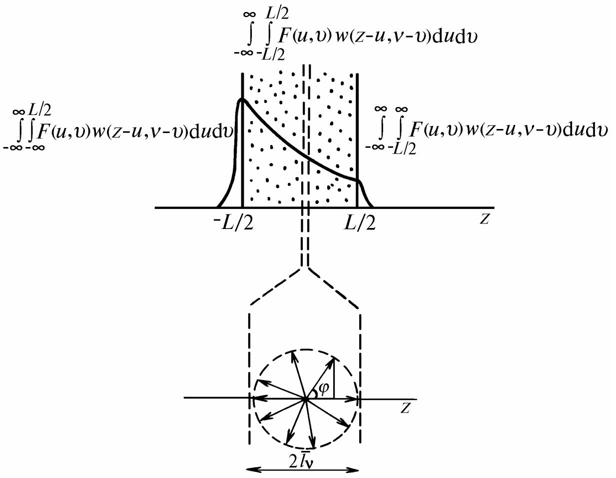

FIG. 2. Illustrative diagram of the calculational technique.

Let us isolate in the cell a sufficiently thin layer with the thickness of the order of the diameter of a cesium atom and determine the spatial distribution of atoms excited by the fluorescence within this layer in the process of single event of reemission. Let also the coordinate system (x, y, z) be oriented in such a way that its origin is at the center of the layer, while its z axis is normal to it. It is obvious that the coordinate of a photon once emitted by an excited atom in the layer and then absorbed by the next atom on its path is determined as follows:

$$z = l \cos\varphi , \tag{2}$$

where l is the photon path length and φ is its azimuthal angle (see Fig. 2). An instantaneous disposition of atoms can be regarded as frozen during an individual reemission act Δt. For this reason the probability distribution function $w(l)$ obeys the Rayleigh law

$$w(l) = \frac{l}{\sigma_\nu^2} \exp(- l^2/2\sigma_\nu^2) , \tag{3}$$

where the variance $\sigma_\nu = \bar{l}_\nu (2/\pi)^{1/2}$, while $\bar{l}_\nu$ is the mean free path of the photon with frequency ν along the direction of the trajectory that is proportional to the mean interatomic distance. At the same time, the dependence of $\bar{l}_\nu$ on ν is inverse compared to the Lorentzian. Since the fluorescence reemission of radiation by atoms is isotropic the statistics over φ is equiprobable, we have

$$w(\varphi) = 1/2\pi , \ 0 \le \varphi \le 2\pi . \tag{4}$$

By combining Eqs. (2) and (4) it is not difficult to show that the distribution over z is the Gaussian,[3] i.e.,

$$w(z, \nu) = \frac{l}{2\pi s_\nu} \exp(- z^2/2\sigma_\nu^2) . \tag{5}$$

The following step in our consideration is the transition to the single-coordinate pattern in which $w(z, \nu)$ is in fact the function of scattering in a thin layer. If the initial distribution of excited atoms was described by the function $F_0(z, \nu)$ determined in accordance with Eq. (1) (here z is already connected with the cell rather than with any particular layer), then, after the first reemission act, the function $F_1(z, \nu)$, because of the linearity and spatial invariance of the problem, is defined as the convolution integral

$$F_1(z, \nu) = \int\limits_{-\infty}^{\infty}\!\!\int F_0(u, \upsilon)\, w(z - u, \nu - \upsilon)\, \mathrm{d}u\mathrm{d}\upsilon . \tag{6}$$

Inside the cell lying in the interval $0 \le z \le L$ for some nth reemission act, we have

$$F_n(z, \nu) = \int\limits_{-\infty}^{\infty}\int\limits_{0}^{z} F_{n-1}(u, \upsilon)\, \{(z - u, \nu - \upsilon)\, \mathrm{d}u\mathrm{d}\upsilon . \tag{7}$$

Based on this recurrent relation one can perform a numerical simulation with relative ease because the calculation of two-dimensional convolution is a standard procedure which is sufficiently widely used in practice.

After the single reemission act, i.e., after one calculational step some portion of radiation escapes the cell ($F_n(z, \nu) \ne 0$ at $z > L$ and $z < 0$) and participates no longer in the further process of reemission. However just this portion of radiation is of greatest interest for us because it makes the instantaneous power of the pulses escaping from the cell to its left and to its right. For this reason in the course of calculations at each step the integrals were calculated

$$I_l(n) = \int\limits_{-\infty}^{0} F_n(z, \nu)\, \mathrm{d}z \ ; \ I_r(n) = \int\limits_{L}^{\infty} F_n(z, \nu)\, \mathrm{d}z \tag{8}$$

using which the shape of pulses of the fluorescence radiation $I_l(t)$ and $I_r(t)$ escaping from the cell to its right and to its left was determined. Here $t = n(\Delta t + T_1)$, $\Delta t = \bar{l}_\nu/c$, c is the speed of light.

In its turn, the conversion coefficient of the filter is defined as follows:

$$\eta = \frac{\theta}{1 - \exp(- K_s L)} \frac{\sum\limits_{n=1}^{n_{\max}} I_r(n)}{\sum\limits_{n=1}^{n_{\max}} \left(I_r(n) + I_l(n)\right)} , \tag{9}$$

where θ is the quantum efficiency of the fluorescence.

The maximum number of steps $n_{\max}$ was found in the course of calculations by a decrease of I_l and I_r with growth of n. The calculations terminate at the moment when $I_{r,l}$ reach negligibly small values that do not contribute essentially into sum (9).

Establishing the applicability limits of our consideration one more assumption should be mentioned. By dividing the calculation procedure into some discrete steps under assumption that all atoms reemit simultaneously with the repetition rate $1/\Delta t$. Of course, actual situation will be different owing to the spread in the magnitudes of $\overline{l}$ and T_1. However, such an approach is justified if $\Delta t\ n_{\max} < T_1$ that is close to reality.

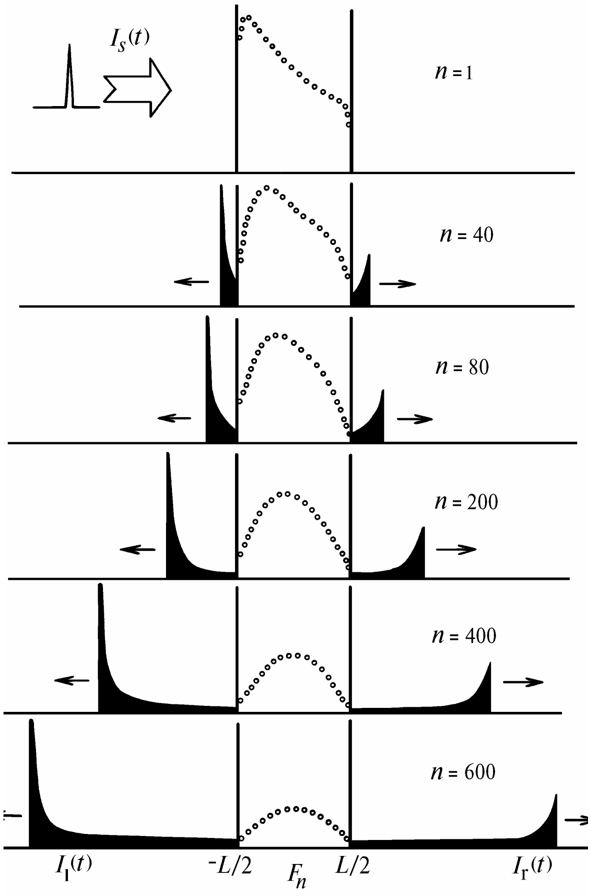

FIG. 3. Kinetics of change of the density of excited atoms (open circles) and temporal shape of the fluorescence pulses $I_r(t)$ and $I_l(t)$ *for the case of the cell excitation by a short signal pulse* ($K_s L = 1$).

The results of numerical simulations are presented in Figs. 3–6. As an illustration, Fig. 3 shows the dynamics of changes in the distribution of excited atoms over the cell depth and temporal profiles of the fluorescence radiation pulses $I_l(t)$ and $I_r(t)$ calculated for $n = 20$ (reemission acts). When estimating the duration of the fluorescence pulses one should keep in mind that each calculational step corresponds to the time interval $\Delta t = \overline{l}_v/c + T_1$, where T_1 is determined by the pressure of a buffer gas in the cell. For pure cesium vapor $T_1 = 30$ ns. With an addition of a buffer gas the T_1 value decreases in the inverse proportion to its pressure $T_1 \sim p^{-1}$ (where p is in mm Hg).

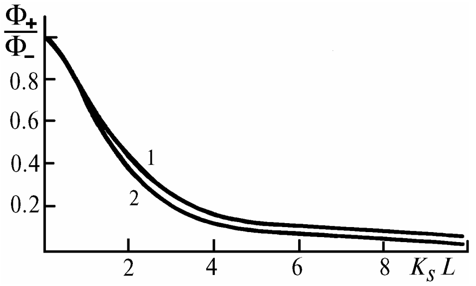

FIG. 4. Ratio of pulse energies of the atomic fluorescence radiation propagating counter to ($\Phi\_$) *and along the direction* (Φ_+) *of the signal radiation: 1)* $K_f = 70\ K_s$ *and 2)* $K_f = K_s$.

In Fig. 4 the ratio of energies of the fluorescence $\Phi_\text{þ} = \int I_{r,l}(t)\mathrm{d}t$ emitted from the cell in the directions to the left and to the right of the cell, is plotted versus the cell optical density at the signal frequency. It is obvious from the figure that from the optically dense cell ($K_s L > 5$) the major portion of the fluorescence radiation (> 80%) is reemitted in the backward direction towards the signal pulse. Based on this fact an optimization of construction of the atomic–resonance fluorescence filter can be carried out with respect to the transmission coefficient and operation rate as well as the pass band of the post photodetector electronics and can be chosen. For this purpose an additional cell–reflector filled with cesium vapor is placed in front of the cell–converter *2* (see Fig. 1*b*) and the pressure of a buffer gas in the cell–reflector is A times higher than in the converter–cell. As a result, the absorption transmission band $\Delta\nu_0$ is correspondingly A times narrower, although at the wavelength of the fluorescence it still remains optically dense ($K_f L > 3$). Principle of operation of the reflecting cell is the following: the fluorescence radiation reemitted from the converter cell in the backward direction is fully absorbed in the reflecting cell and, in its turn, it is mostly directed backwards from the reflecting cell, i.e., in the direction toward the photodetector. Because the spectral broadening of the radiation reemitted from the reflecting cell is larger this radiation by a factor of A is absorbed only weakly in the converter cell and will reach the photodetector practically without losses. The transmissivity of the reemitting cell for the spectrally broadened radiation of fluorescence from the reflecting cell is expressed by the relations

$$\tau_1 = \int\limits_{-\infty}^{\infty} \frac{\exp\left(-K_f L/(1+x^2)\right) \mathrm{d}x^2}{(x/A - \delta/A)^2 + 1} \Bigg/ \int\limits_{-\infty}^{\infty} \frac{\mathrm{d}x}{(x/A - \delta/A)^2 + 1}, \tag{10}$$

when the buffer gas is in both cells, and

$$\tau_2 = \int\limits_{-\infty}^{\infty} \frac{\exp\left(-\pi^{-1/2} K_f L/\exp(-x^2)\right) \mathrm{d}x^2}{(x/A - \delta/A)^2 + 1} \Bigg/ \int\limits_{-\infty}^{\infty} \frac{\mathrm{d}x}{(x/A - \delta/A)^2 + 1}, \tag{11}$$

when the converter cell contains pure cesium vapor. Here $x = (\nu - \nu_0)/\Delta\nu_{\rm ab}$, $\Delta\nu_{\rm ab}$ is the absorption bandwidth in the converter cell, while $\delta = (\nu_{\rm max} - \nu_0)/\Delta\nu_{\rm ab}$ is the normalized shift of the maximum of the absorption line caused by a buffer gas[4] (see Fig. 5).

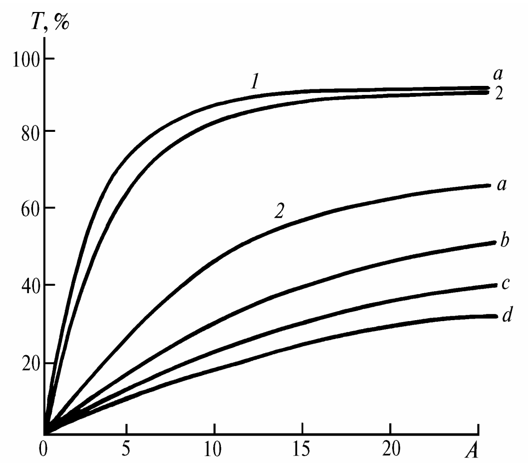

FIG. 5. Transmissivity of a converting cell for the case of the spectrally broadened radiation from the reflecting cell, (0), $A = \Delta\nu_{\rm r}/\Delta\nu_{\rm ab}$: *1) the converting cell contains pure cesium vapor, 2) the same as in (1) but with an addition of a buffer gas: a, b, c, and d refer to* $K_s L_{\rm abs}$ = 1, 3, 6, *and* 9, *respectively.*

Now, based on the calculations performed for the case of a single cell the conversion coefficient η_2 can be found for the case of such a coupled construction of an ARFF. Figure 6 shows the calculational results which were obtained for different ratios A of pressures of a buffer gas in the cells and for the ratio of the cell thickness $B = L/L_{\rm o} = 1$. Here $L_{\rm o}$ is the thickness of the reflecting cell. For the converting cell it was set that $K_f = 70\,K_s - \Delta$, while for the reflecting cell $K_s = K_f$. Also depicted in this figure is the conversion coefficient η_2 for an ARFF with a single–converting cell that is illustrative of the fact that the choice of optimal parameters would allow one to improve the efficiency of the ARFF by more than 2 times.

Thus, numerical simulation according to the above method of the kinetics of the resonance radiation from the cell with atomic vapor allowed us to estimate the duration and the fluorescence pulse energy, as well as to calculate the conversion coefficients of the atomic–resonance fluorescence filters of different constructions.

In conclusion we should like to note that the above–discussed method can be generalized for the case of excitation of the filter by a stationary radiation or by pulses whose duration exceeds the characteristic times T_1, T_2, and T^*, where T_2 is the lifetime of the upper level of a radiative transition in cesium, while T^* is some effective time of delay of the luminescence that is attributed to the reemissions. In fact we have already calculated this value in the above nonstationary model of response of a system to a δ–pulse and it is determined as the characteristic duration of the radiation escaping from the cell in this case (see, for example, Fig. 3).

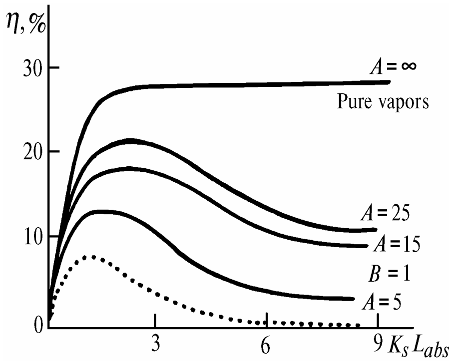

FIG. 6. The calculated conversion coefficient for the construction of the ARFF with the reflecting cell. Ratio of the cell thicknesses ($B = L_{\rm abs}/L_{\rm o}$)*; the coefficient of transformation of the ARFF with a single cell.*

In the case of stationary illumination of the filter a uniform distribution of the excited atoms over the cell length is established. Owing to the effect of radiation capture the absorption coefficient K_s^* decreases in comparison with nonreemitting case (K_s) because of effective increase of the resonance lifetime T_1, i.e.,

$$K_s^* = K_s T_1/(T_1 + T^*)\ . \qquad (12)$$

Now it is not difficult to obtain the ratio of fluorescence fluxes escaping to the left and to the right of the cell. Because the situation is stationary this quantity is determined the ratio of the amounts of excited atoms at the boundaries of the layer that is equal to

$$\Phi_+/\Phi_- = \exp\,(-\,K_s^*\,L)\ . \qquad (13)$$

Here we used relation (1) modified for the case of the effective absorption coefficient K_s^*.

REFERENCES

1. A.M. Prokhorov, ed., *Laser Reference Book* (Sovetskoe radio, Moscow, 1979), Vol. 2, 400 pp.
2. O.I. Matveev, Zh. Prikl. Spektrosk. **46**, No. 3, 359–375 (1987).
3. C.A. Akhmanov, Yu.E. D'yakov, and A.S. Chirkin, *Introduction into Statistical Radio Physics and Optics* (Nauka, Moscow, 1981), 640 pp.
4. Sh. Chen and M. Takeo, Usp. Fiz. Nauk, No. 3, 391–407 (1958).