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► **To cite this version:**

H. Guillet De Chatellus, J. P. Pique. $\lambda/2$ fringe-spacing interferometer. Optics Letters, 2009, 34, pp.755. 10.1364/OL.34.000755 . hal-00951774

HAL Id: hal-00951774

<https://hal.science/hal-00951774>

Submitted on 27 Feb 2014

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A $\lambda/2$ fringe spacing interferometer

H. Guillet de Chatellus and J.-P. Pique

Laboratoire de Spectrométrie Physique UMR 5588 CNRS-Université Joseph Fourier, 140 Av. de la Physique, BP 87 - 38402 Saint Martin d'Hères, France

* Corresponding author: hguillet@spectro.ujf-grenoble.fr

Compiled January 20, 2009

The precision of interferometry is directly linked to the fringe spacing of the recorded interferogram. Whereas all interferometric devices show a fringe spacing equal to a wavelength of the laser light we present a novel scheme of two-beam interferometer exhibiting a fringe spacing reduced by a factor of two: the direct detection of the beat signal is replaced with the monitoring of the fluorescence of a two-fold degenerate atomic system resonant with the laser. The $\lambda/2$ fringe spacing in the fluorescence signal is demonstrated with a hot sodium vapor excited by a broadband laser tuned to the D_1 line. In the saturation regime, the dark fringes are expected to be extremely narrow leading to the possibility of nanoscale displacement measurements or atom localization.

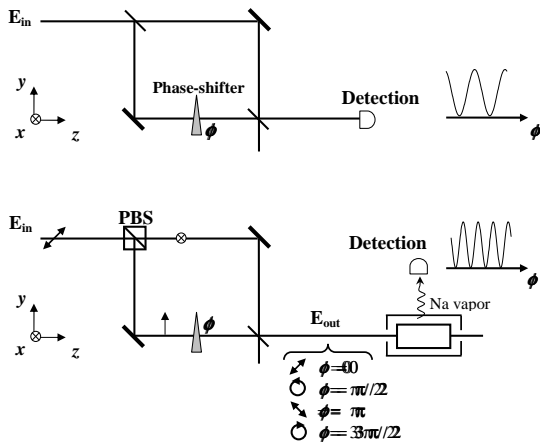


Fig. 1. Top: generic two-beam interferometer: ϕ is the phase shift between both beams. Bottom: Mach-Zehnder interferometer using the monitoring of the resonant fluorescence as the beat signal (see text).

Beside its fundamental interest for illustrating the wave nature of light, two-beam interferometry is a widely spread tool for precise position measurements at the nanometer scale [1]. Briefly, a laser beam at the wavelength λ is split in two arms having respectively a fixed optical length (l_0) and a variable one (l). When both beams are recombined, the resulting phase shift is $\phi = 2\pi(l - l_0)/\lambda$. Within the coherence length of the laser, the beat signal cancels periodically when l is varied and the fringe spacing (*i.e.* the distance l has to be varied to reach the next fringe) is simply λ . This result can be extended to any kind of two-beam interferometer and constitutes actually a fundamental limitation for displacement measurements since the resolution is directly proportional to the fringe spacing.

Here we propose a method based on elementary as-

pects of atomic physics to reduce the fringe spacing by a factor of two. We consider a laser beam polarized at 45° whose wavelength is tuned to a $J = 1/2 \rightarrow J = 1/2$ atomic transition (Fig. 1). A polarizing beam splitter (PBS) divides the beam into two balanced orthogonally polarized modes. In the variable arm the mode experiences a phase shift ϕ with respect to the reference one and both polarizations are recombined at the output. The direct detection of the beat signal by a photodiode is replaced with the monitoring of the fluorescence emitted by the atomic vapor resonantly excited by the laser. When $\phi = 0$ or π , the resulting polarization is linear at 45° and 135° and the resulting π excitation of the atom (for a quantization axis in the direction of the resulting polarization of the laser) induces continuous cycles of absorption-fluorescence. However for $\phi = \pi/2$ or $3\pi/2$, the resulting polarization is circular (*i.e.* σ excitation for a quantization axis along the direction of propagation of the laser) and the atom is optically pumped onto one of the dark states $|m_J = +1/2\rangle$ or $|m_J = -1/2\rangle$. Therefore the fluorescence vanishes twice per period of ϕ , leading to a $\lambda/2$ fringe spacing in the fluorescence signal. This paper is dedicated first to the theoretical description of this unusual phenomenon by using a rate equations model: the $\lambda/2$ period is demonstrated and extremely sharp variations of the fluorescence with the phase are predicted in the strong saturation regime, leading to possibilities in highly sensitive interferometry or atom localization. Then we present the experimental demonstration of a $\lambda/2$ fringe spacing Michelson interferometer, where the fluorescence produced by a sodium vapor resonantly excited by a broadband modeless laser tuned to the D_1 line shows a $\lambda/2$ fringe spacing. Finally we extend this result to the spatial domain by creating an interference pattern with a fringe spacing divided by two compared to an usual interference grating.

First we consider a laser field of amplitude E_0 polarized at 45° at the input of a Mach-Zehnder interferome-

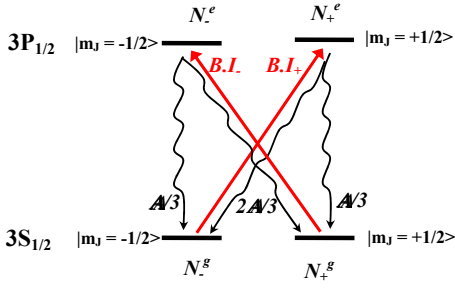


Fig. 2. Fine structure of the sodium D_1 line. A is the rate of spontaneous emission ($=1/16$ ns), B is the Einstein coefficient for the σ transitions.

ter. The beam is split by a polarizing beam splitter: the x polarization travels in the reference arm and the y polarization in the variable arm, where it experiences a phase shift of ϕ . The field at the output of the interferometer is simply:

$$\mathbf{E}_{\text{out}} = E_0/\sqrt{2} \begin{pmatrix} 1 \\ e^{i\phi} \end{pmatrix} \text{ in the } \begin{pmatrix} x \\ y \end{pmatrix} \text{ basis.}$$

It is convenient to express the components of \mathbf{E}_{out} in the basis of left and right circular states of polarization $\begin{pmatrix} 1/\sqrt{2} \\ i/\sqrt{2} \end{pmatrix}$ and $\begin{pmatrix} 1/\sqrt{2} \\ -i/\sqrt{2} \end{pmatrix}$: one obtains respectively $E_0(1 - ie^{i\phi})/2$ and $E_0(1 + ie^{i\phi})/2$. The intensities I_l (resp. I_r) of left (resp. right) circular polarizations are equal to $I_0(1 + \sin\phi)/2$ (resp. $I_0(1 - \sin\phi)/2$), where $I_0 = E_0^*E_0$.

Assuming a quantization axis along z , I_l and I_r correspond respectively to I_- and I_+ , the intensities of σ^- and σ^+ polarizations (Fig. 2). Since the excitation paths are decoupled, the system can be described by a rate equations model. (Note that a Bloch equations description led to the same $\lambda/2$ periodicity in the case of the coherent control of light shift in a similar atomic system [2].) We neglect any absorption and assume that the laser fields seen by the atom in the vapor cell are I_- and I_+ : the atom experiences two antagonistic optical pumpings whose relative weight depends on ϕ . We define the probabilities of occupancy of the relevant sub-levels $N_+^g, N_-^g, N_+^e, N_-^e$ where the superscripts stand for "ground" or "excited" and the subscript for the sign of the spin projection on the z axis. A and B are the usual Einstein coefficients [3]. The rate equations system is:

$$\begin{aligned} \dot{N}_\mp^e &= BI_\mp N_\pm^g - BI_\mp N_\mp^e - AN_\mp^e \\ \dot{N}_\mp^g &= -BI_\pm N_\mp^g + BI_\pm N_\pm^e + (A/3)N_\mp^e + (2A/3)N_\pm^e \end{aligned} \quad (1)$$

In the steady state regime, the populations of the ground and excited levels are:

$$N_+^g + N_-^g = \frac{\cos^2\phi + 2I_{\text{sat}}/I_0}{2\cos^2\phi + 2I_{\text{sat}}/I_0} \quad (2)$$

and

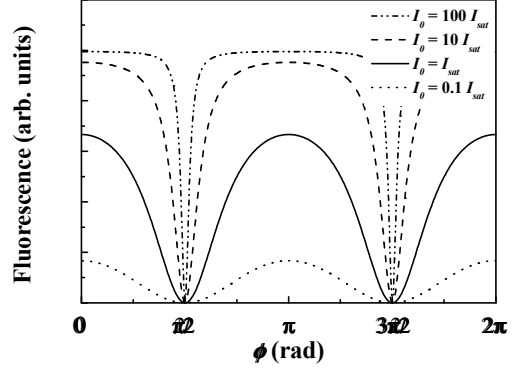


Fig. 3. Variation of the fluorescence signal with the phase shift for different values of the saturation parameter.

$$N_+^e + N_-^e = 2N_+^e = \frac{\cos^2\phi}{2\cos^2\phi + 2I_{\text{sat}}/I_0} \quad (3)$$

where $I_{\text{sat}} = A/B$ is the saturation intensity of the transition. The fluorescence is proportional to the population of the excited state and plotted on fig. 3 for different values of the saturation parameter. Note the π periodicity of the fluorescence signal and the close similarity with the Airy function. In the linear regime where the laser intensity is kept far below the saturation, the fluorescence evolves as $\cos^2\phi$. As expected, it vanishes for $\phi = \pi/2$ and $3\pi/2$ (circular polarizations) and is maximal for $\phi = 0$ or π where the resulting polarization is linear. In the regime of strong saturation, the fluorescence becomes anharmonic: the fluorescence is highly sensitive to phase in the vicinity of $\phi = \pi/2$ and $\phi = 3\pi/2$ which can be of great interest for very high resolution displacement measurements or determination of atom positions. Interestingly our results are quite similar to a recent proposal for nanoscale atom localization based on coherent population trapping [4]. Our scheme however shows greater simplicity than previously proposed localization schemes ([4] and references therein).

The second part of the paper is dedicated to the experimental demonstration of this unusual interferometric device. We consider a sodium vapor excited on its D_1 line ($3S_{1/2} \rightarrow 3P_{1/2}$ at 589.6 nm). Optical pumping between hyperfine levels can be neglected provided the laser spectrum covers the whole hyperfine width of the transition. In that case the description of the transition by the fine structure is sufficient. We have used in this study the same 589 nm dye laser initially developed for the problematic of artificial guide stars in astronomy [5]. It delivers a continuous spectrum covering the whole Doppler-hyperfine width of the D_1 or D_2 lines of the sodium atom. This frequency shifted feedback (or modeless) laser relies on the insertion in the cavity of an acousto-optics frequency shifter preventing the establishment of usual cavity interferences [6]. It delivers up to 100 mW with a continuous spectrum whose width is nar-

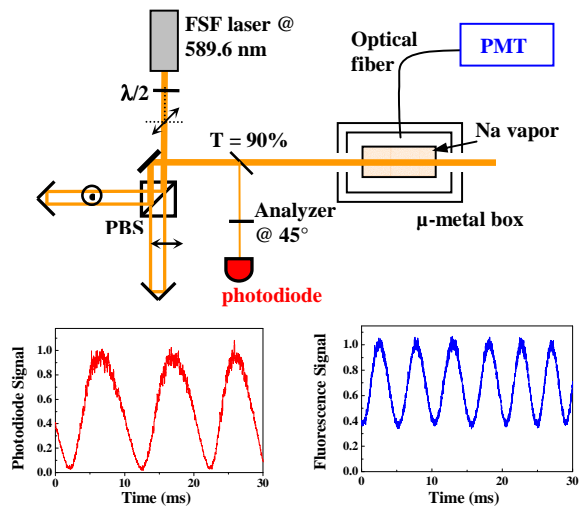


Fig. 4. Top: Sketch of the Michelson interferometer. Bottom left: intensity transmitted across the analyzer at 45° during a scan of the translation stage. Bottom right: fluorescence signal recorded for the same scan.

rowed to 3 GHz (*i.e.* the whole Doppler-hyperfine width of the D_1 line) by intracavity selective elements.

The 40 mW laser beam is polarized at 45° and sent onto a PBS to feed both arms of the interferometer. The phase shift is tuned by means of a translation plate, within the coherence length of the laser field. Then the orthogonally polarized beams are recombined on the PBS and sent through the sodium cell. A small part of the beam is sent through an analyzer at 45° and detected by a photodiode. The 5 cm pure vacuum sodium vapor cell is placed in an oven at 100°C . At this temperature the absorption of the laser by the vapor is weak. Under our experimental conditions, the saturation parameter per velocity class is kept below 1. The apparatus is screened from the ambient magnetic field by a double μ -metal shield to avoid redistribution of the atomic populations due to Zeeman effect. A multimode optical fiber picks the fluorescence photons to a photomultiplier tube (PMT). The fluorescence signal is recorded on the oscilloscope and compared to the beat signal from the photodiode. Both signals are plotted on fig. 4. As expected, the photodiode signal exhibits the usual 2π periodic beating of two-beams interferometers whereas the fluorescence signal shows a reduction of the fringe spacing by a factor of two. The strong CW background on the fluorescence signal is due to the fact that the atom fly across the laser beam on a time scale comparable to the optical pumping time. It could be substantially reduced by any method to confine the sodium atoms in the laser beam such as the use of a buffer gas or a paraffin coated cell preserving the atomic state during the collisions with the walls [7].

Finally we carried out a direct observation of the frequency doubling of the interference pattern in the

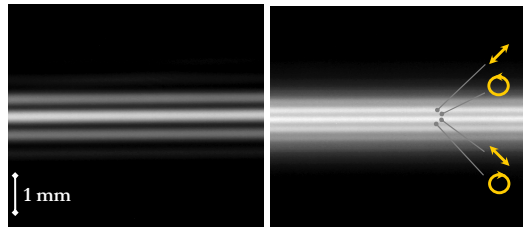


Fig. 5. Left (resp. right): fluorescence pattern seen from the top of the sodium cell when both beams overlap with an angle of 1 mrad with parallel (resp. perpendicular) polarizations.

spatial domain. The interferometer is slightly modified and both beams overlap in the vapor in the horizontal plane with an angle $\alpha = 1\text{mrad}$. The fluorescence resulting from the interference is observed through an imaging system and a CCD camera. When both polarizations are identical, usual intensity interference fringes are recorded and show a fringe spacing $\lambda/[2\sin(\alpha/2)]$. When the beams have perpendicular polarizations, the polarization grating is revealed by the atoms and a doubling of the spatial interference pattern is observed (fig. 5). Dark fringes correspond locally to a circular polarization ($\phi = \pi/2, 3\pi/2$) whereas bright fringes correspond to a linear one ($\phi = 0, \pi$). The fluorescence pattern is the signature of a grating of atomic angular momentum.

In conclusion we investigated both theoretically and experimentally a new type of interference device where the direct detection of the beat signal is replaced with the monitoring of the resonant fluorescence emitted by a two-fold degenerate two level atomic system resonantly excited by a modeless laser. The combination of this new laser source and detection scheme shows unexpected properties compared to the direct detection by a photodiode: the fringe spacing is reduced by a factor of two and applications in ultra sensitive atomic positions measurements are foreseeable in the strong saturation regime.

This work was supported by the CNRS and the Région Rhône-Alpes. We thank Thibaut Vacelet for helpful technical support.

References

1. P. Hariharan, "Optical Interferometry", 2nd ed. (Academic, San Diego, 2003).
2. J. C. Delagnes and M. A. Bouchene, Phys. Rev. Lett. **98**, 053602 (2007).
3. R. Loudon, "Quantum Theory of Light", 3rd ed. (Oxford U. Press, New York, 2000), Chap. 1.
4. G. S. Agarwal and K. T. Kapale, J. Phys. B: At. Mol. Opt. Phys. **39**, 3437 (2006).
5. J.-P. Pique and S. Farinotti, J. Opt. Soc. Am. B **20**, 2093 (2003).
6. L. P. Yatsenko, B. W. Shore and K. Bergmann, Opt. Comm. **236**, 183 (2002).
7. W. Happer, Rev. Mod. Phys. **44**, 169 (1972).