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Antennaless 3D Sensors for Direction of Arrival estimation Based on Rydberg Atoms.

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Abstract

Antenna-arrays for Direction-of-Arrival (DOA) estimate are heavily limited by mutual coupling among sensors and between sensors and the installation environment. Huge efforts are devoted for calibration-based techniques that result not always decisive about compensating these unwanted coupling effects. In this paper we describe a possible application of Rydberg-atoms based sensors in the field of the DOA estimation. A principle fully-dielectric miniaturized 3D interferometer is presented, capable of providing both azimuth and elevation estimate of an incoming electromagnetic (EM) wave front thus overcoming the aforementioned limitations due to metal-based EM sensors (i.e. antennas).

1 Introduction

Recently sensors based on Rydberg atoms [1] have been made technically possible and available [2]. These type of sensors rely on a vapor of atoms having one or more electrons excited to a very high principal quantum number *n*. This excited Rydberg atoms exhibits strong and interesting electric and magnetic properties, for example, their have a large dipole moment, proportional to n^2, which makes them sensitive to the electric field.

The basic idea is that of exploiting a technique known as electromagnetically induced transparency (EIT) and Autler-Townes (AT) splitting to detect a radio-frequency (RF) E-field, in particular, due to the recent change in the definition of the system of units (Sisteme Internationale – SI) [3]. Indeed, due to the fact that Rydberg atoms detection of the electric field is directly proportional to Plank constant – which is now a fixed exact value – its amplitude measure via this technique is particularly promising [4].

Phase measurements, on the other hand, received much less attention until the very recent development of a Rydberg atom-based mixer [5] and its further improvement [6].

In [6] it is shown that, by placing the Rydberg-atom vapor cell within a parallel-plate waveguide (PPWG) antenna, both amplitude and phase of an incoming signal can be detected for an incident phase-modulated signal.

In this contribution we will try to devise a Direction-of-Arrival (DoA) set-up based on a Rydberg atoms detector similar to those presented in [5,6]. Expected advantages are the extremely large band on which the sensor works, spanning from 100MHz to 1THz [7] (indeed it could go much lower in frequency bt exploiting a different system, but this requires very strong electric field, which are not of interest for a DoA application). At the same time the sensors an extremely small, mm in size, self-calibrating and fully dielectric, hence with no mutual coupling between neighboring sensors.

2 Rydberg-atom detector

Rydberg atoms detector are usually based on high atomic-number alkali metal atoms, like 133Cs and 85Rb, since in this atoms the single outer s-shell electron is weakly bounded to the nucleus due to the other electrons' shielding. It is hence possible to achieve high principal quantum number n states in the Rydberg series by optical excitation with commercially available lasers [7].

The basic operating principle is that of EIT. This is implemented by two lasers, a probe laser, at a wavelength chosen so as to couple the ground state of the atoms to an intermediate state (for instance, a red laser at a wavelength of 780nm) and a coupling laser, coupling such intermediate state to an appropriate Rydberg state (for instance, a higher energy blue laser at 480nm of wavelength, see Fig. 1).

The presence of both laser overlapping across the cell results in a coherence that causes a decrease in the absorption of the probe laser. This lower absorption, and hence higher transmission through the cell is known as EIT. When the atoms are excited to a high energy Rydberg state, they are very sensitive to RF fields, since Rydberg states are very close one to the other and hence the relatively weak photons associated to the RF field can cause a further transition (Fig. 1).

The presence of an external RF field, then, alters the transmission spectrum of the probe laser, which can be used to detect amplitude and phase of the RF E-field.

One of the two lasers must scan in wavelength, either the probe laser or the coupling laser. Fig. 2 shows what happens: in absence of any RF electric field there is a maximum of the EIT at the nominal value of the two lasers wavelength and a reduced EIT as one of the two lasers is detuned.

In presence of a third electromagnetic field, the incident RF electric field transition is tuned to a further Rydberg atomic transition (Fig. 1), and the original transparency region is split into two regions separated in frequency, a phenomenon known as Autler-Townes splitting; which increases with increasing applied E-field strength [7].

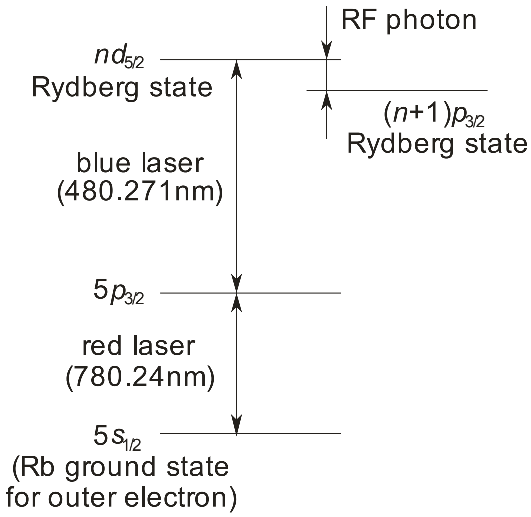


Figure 1. Basic scheme for EIT within an alkaly vapor of Rydberg atoms cell.

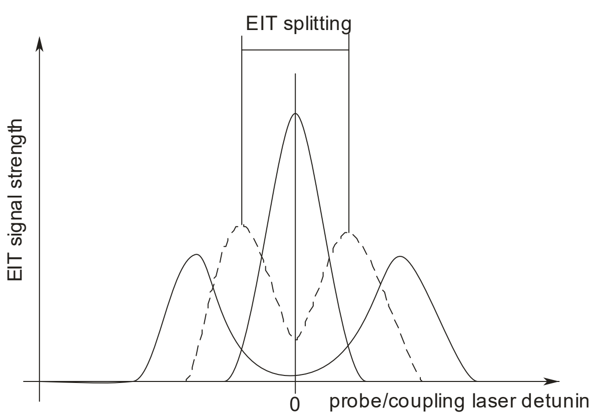


Figure 2. Basic concept for EIT splitting in frequency, as a function of the detuning of one of the two lasers, induced by the presence of an RF electric field.

Finally, if two incident fields are present, a field to be measured and a locally produced RF field which can be considered as a "local oscillator." Such a local oscillator is tuned at a Rydberg transition which, in turn, is de-tuned by the incoming RF field to be measured, generating a beat note which, in a frequency modulated RF field, carries the information on the modulation and the phase difference between the two [8].

3 Rydberg-atom based DoA

A conceptual scheme for a DoA sensor is hence sketched in Fig. 3. A single couple of lasers is used to guarantee locking on all three sensors. A beam splitter divides each laser beam in three, illuminating four vapor cells. Lasers then impinges on a grating separating the probe beam, which is deflected towards a photodetector, from the coupling laser.

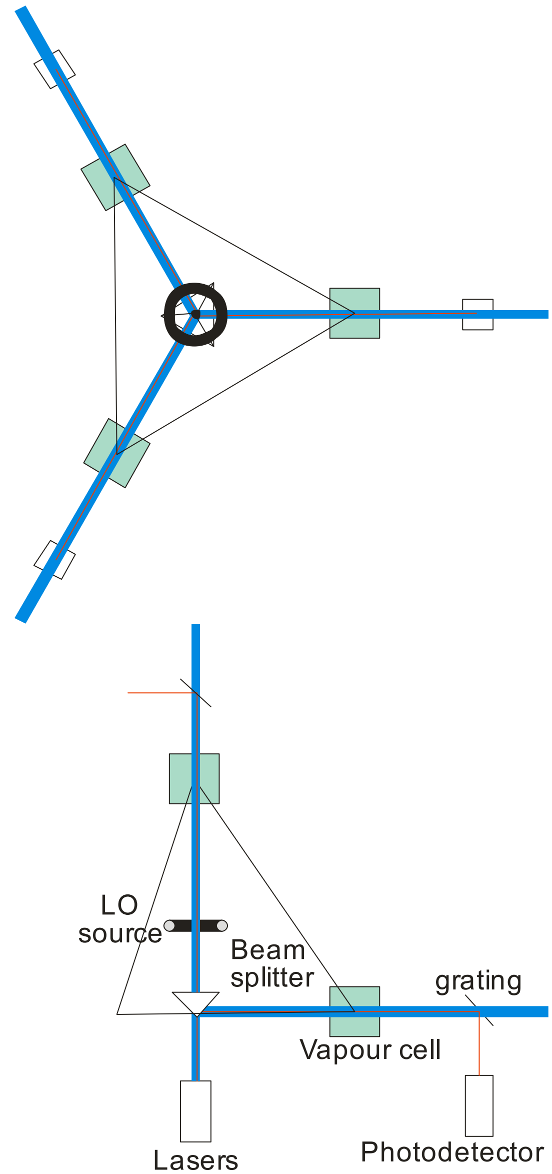


Figure 3. Principle layout for a Rydberg-atom DoA. Top view (top) and side view (bottom).

A single source for the local oscillator field centrally placed is also provided, giving an identical phase reference to the four sensors.

By placing the four sensors at the vertices of a tetrahedron with the appropriate side length of 28 mm and measuring the phase difference between the four sensors it is possible to estimate the direction of arrival of the signal by a correlation-based technique [9] over 2-6 GHz frequency band (the interferometer working band is inherently limited by sensors distances).

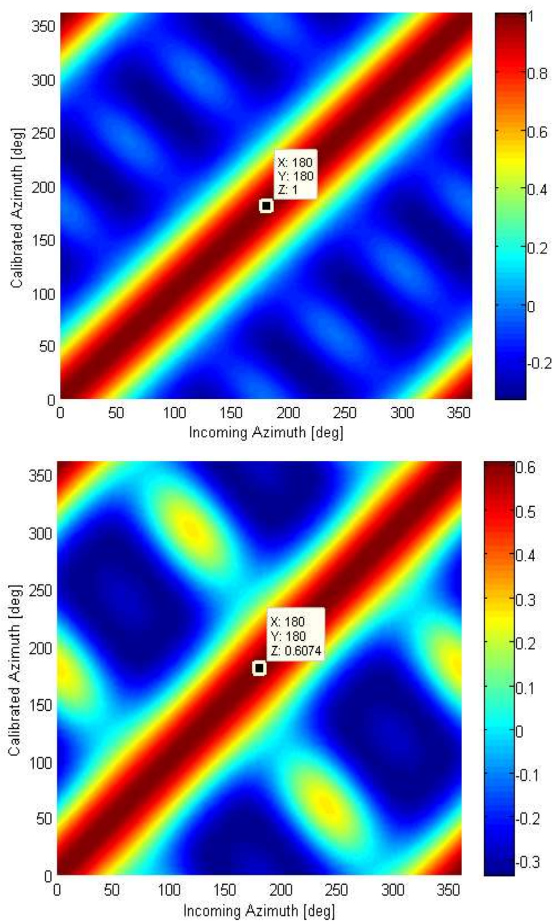
Moreover, by neglecting coupling effects (which in the case of Rydberg sensors are effectively non-existent, while in standard electromagnetic sensors cannot be neglected and whose reduction is generally very difficult and narrow-banded [10]) and in the case of almost omnidirectional sensors, phase difference depend only on the geometrical positions of sensors:

$$\Delta\Phi_{nm} = \frac{2\pi}{\lambda}\hat{\boldsymbol{R}} \cdot (\boldsymbol{r_n} - \boldsymbol{r_m})$$
$$n, m \in \{1, 2, 3, 4\}$$

The correlation function *CF* is then defined as follows:

$$CF\left(\psi_i, \theta_i, \psi_g, \theta_g, \lambda\right) = \frac{1}{N_b}\sum_{b=1}^{N_b} cos\left[\Delta\Phi_{i,b}\left(\psi_i, \theta_i, \lambda\right) - \Delta\Phi_{g,b}\left(\psi_g, \theta_g, \lambda\right)\right]$$

where $\Delta\Phi_{i,b}$ is the incoming set of phase differences and $\Delta\Phi_{g,b}$ the geometrical calculated set of phase differences, used as a reference, b is the actual chosen couple of sensors (m,n), *Nb* is the cardinality of the chosen set of couples of sensors.



(a)

(b)

Figure 4. Correlation fuction plot at 4.5 GHz, obtained by correlating incoming EM wavefronts at 0° elevation to geometrically obtained phase difference at elevation 0° (a) and 30° (b). The maximum of the correlation function is found along the diagonal ad for case (a), thus allowing the estimate of both azimuth and elevation of the impinging wave.

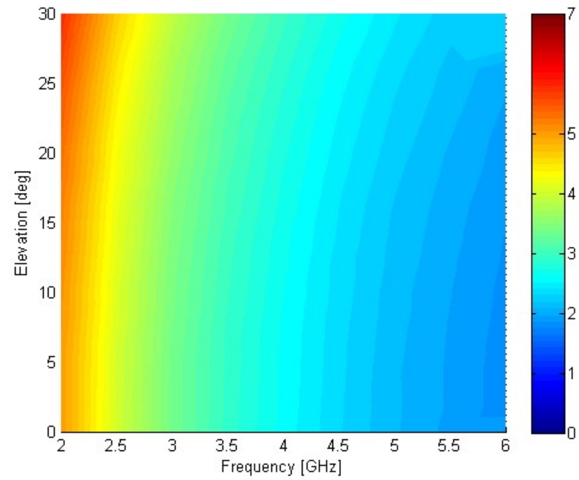


Figure 5. Azimuth DOA RMS Error for the sensor configuration depicted within Fig. 3.

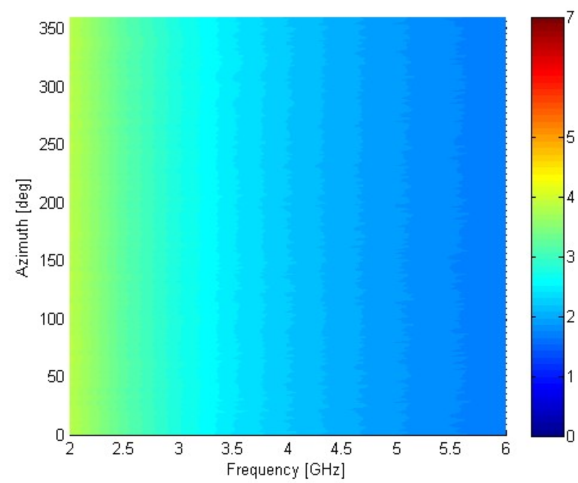


Figure 6. Elevation DOA RMS Error for the sensor configuration depicted within Fig. 3.

The DOA is finally estimated by searching the maximum of *CF*, see for instance the results depicted in Fig. 4.

In the following picture, DOA performances are presented in case of a SNR equal to 15dB, a phase unbalance between channels linearly varying with frequency form 2° to 6°, a gain unbalance between channels linearly varying with frequency form 1dB to 2dB, a number of 6 couples of sensors (2,1), (3,2), (1,3), (4,1), (4,2), (4,3).

4 Conclusions

A tentative layout for DoA exploiting Rydberg atoms sensors has been presented. The design is expected to provide better performances than conventional antennas due to the complete lack of mutual coupling between the sensors and their inherent broadband as well as miniaturization.

7 References

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