We demonstrate a movable, Rydberg atom-based radio frequency (RF) electric (E) field probe. The technique is based on electromagnetically induced transparency and Autler–Townes splitting. Two fibers attached to a 10 mm cubic $^{133}$Cs vapor cell are used to couple counter-propagating probe and control lasers through the cell. This all-dielectric fiber-coupled sensor can be moved from the optics table to locations more suitable for RF (gigahertz to sub-terahertz) E-field measurements and calibrations.

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1. INTRODUCTION

Atom-based radio frequency (RF) electric (E) field metrology solves a chicken-and-egg problem in RF calibrations. Currently, antenna-based RF field probes must be calibrated using a known field, but to create a known field requires a calibrated probe. Furthermore, at high frequencies (above 110 GHz) there are no calibration standards. A solution to these problems is to use resonances in Rydberg atoms to sense the strength of an RF E field. These resonances occur over a large range of frequencies from hundreds of megahertz (MHz) up to terahertz (THz), and the atomic dipole moments over this frequency range can be very large. Specifically, RF E-field strength can be directly measured using Autler–Townes (AT) splitting of Rydberg atom electromagnetically induced transparency (EIT). More details on this method can be found in [1–4].

EIT is achieved through a two-step excitation using probe and control lasers counter-propagating through an alkali vapor cell. The transmission of the probe laser is monitored in response to an externally applied RF field, which splits the EIT transmission peak in two (AT splitting). Measurement of E-field strength is based on the relation between the frequency separation between the two peaks $\Delta f_0$ and the strength of the applied RF field $|E_{RF}|$,

$$|E_{RF}| = 2\pi \frac{\hbar}{\mathcal{P}} \Delta f_0,$$

where $\mathcal{P}$ is the dipole moment of the Rydberg transition, which must be calculated. This converts an absolute amplitude measurement into a relative optical frequency measurement.

There has been much recent work exploring the capabilities of Rydberg EIT for detecting and measuring RF E fields [2–4], examining both very strong [5] and weak [6–8] field detection, as well as RF and THz imaging [9–11]. Thus far, EIT-based RF field measurements have been confined to an optical table where the lasers are overlapped in free space, which limits the ability to isolate the RF fields. This makes it difficult to perform RF E-field measurements under controlled conditions and in more conventional environments, such as anechoic chambers, as the RF source must also be in the presence of the optical table. This ultimately sets a limitation on the utility of the measurement technique, reducing the accuracy of calibrations. There has been development of fiber-based atomic vapor cells for absorption spectroscopy [12], atom spectroscopy in an integrated photonic chip [13], Rydberg state spectroscopy in hollow-core fibers [14,15], cold-atom experiments, and quantum-optics applications [16]. Many of these techniques are very promising for future portable Rydberg atom-based RF metrology devices. Atomic vapor-filled hollow-core fibers are currently confined to larger structures, either vacuum chambers or vapor cells with heating elements, which limit their portability. One important goal is a portable probe that contains no circuitry or strongly scattering metal parts.

To this end we have developed a fiber-coupled, all-glass atom-based RF field probe that is movable and no longer confined to the optical table. In this design the probe and control lasers are counter-propagated and focused through a cubic vapor cell by attaching fibers with gradient-index (GRIN) lenses to the cell. This all-dielectric probe can be moved off the optical bench and placed in shielded environments for more accurate RF field measurements. This will allow for a comparison with existing RF field probes and future integration into RF metrology environments.
2. FIBER-COUPLED VAPOR CELL

For this work we used cesium ($^{133}$Cs) atoms inside a cubic glass vapor cell with 10 mm sides and 1 mm thick walls. The probe laser (852 nm) enters the vapor cell using a pigtailed single-mode fiber (with a cutoff wavelength of ~660 nm) and is focused using a GRIN lens. The control laser (511 nm) enters the opposite side of the vapor cell through a single-mode fiber (with a cutoff wavelength of ~500 nm), output through another GRIN lens. The control laser fiber also serves as the return fiber for the probe laser. Figure 1 shows a photo of the completed probe. The control laser input to the fiber and the probe laser output from the fiber were split using a dichroic mirror, directing the probe laser to a detector. The distances between the fiber ends and the GRIN lenses were first adjusted to maximize the probe laser transmission through both fibers. Without the vapor cell, the maximum coupling of the probe laser through both fibers that we achieved was 30%, with a minimum distance between the fibers of 12 mm. We then inserted the Cs vapor cell in between the fibers and re-adjusted the distance between the fibers and the GRIN lens-to-fiber distances to optimize the EIT signal and EIT linewidth. This resulted in a reduction of the probe laser coupling efficiency to 17%, as detailed below.

GRIN lenses are defined by the length $l_G$ and diameter $d_G$ of the lens, the base index $n_0$ (at the center of the lens), and the gradient constant $A$. The GRIN lens parameters for the probe fiber are $l_G = 4.35$ mm, $n_0 = 1.5986$, and $\sqrt{A} = 0.332$ mm$^{-1}$, while for the control fiber they are $l_G = 4.26$ mm, $n_0 = 1.6073$, and $\sqrt{A} = 0.339$ mm$^{-1}$; both are $d_G = 1.8$ mm.

The distance between the probe fiber and probe GRIN lens was set to 0.5 mm, creating a beam waist (full width at half-maximum, FWHM) of $d = 18$ μm at a distance of 10 mm from the end of the GRIN lens (Fig. 2). The beam diameters were measured at several points in between the fibers using a knife-edge technique with the vapor cell removed. The spacing between the control laser fiber end and the control laser GRIN lens as well as the separation between the two GRIN lenses was adjusted to maximize the probe laser signal. The best signal was obtained at a spacing between the control fiber end and the GRIN of 0.6 mm and a GRIN–GRIN separation of 20 mm. The GRIN lenses were attached to the fiber ends with a ultraviolet (UV) epoxy. The fibers were then placed inside plastic sleeves for stability and realigned through the Cs vapor cell.

These assemblies were attached to the vapor cell using the UV epoxy while monitoring the EIT signal. The transmission efficiency of the 511 nm control beam into the vapor cell was 34%. For the 852 nm probe, 76% was transmitted through the input fibers into the vapor cell, and the total efficiency through the system (input fiber, vapor cell, and output fiber) was 17%.

The design parameters for a Rydberg atom-based RF field probe are constrained by several factors: the probe must be made from all-dielectric material (no metal), the EIT linewidth cannot be too large (compared to the Rabi frequency of the RF field), and the probe laser must be coupled back through the control fiber such that it can be detected. With such constrained design parameters, a trade-off must be made between optimizing the beam size inside the vapor cell and coupling the probe beam into the return fiber. Optimal coupling of the probe beam into the return (control) fiber with the fibers separated by the length of the vapor cell requires a small probe beam waist. As the beam waist is reduced, there are two effects that broaden the EIT line: transit time broadening and power broadening. The width of the EIT line governs sensitivity, where the weakest detectable splitting is equal to the FWHM of the EIT line. In a room temperature vapor cell, the EIT linewidth is limited to a minimum of ~6 MHz [17]. Transit time broadening ($\Gamma_t$) is given by the mean velocity of the atoms ($v$) as they pass through the beam of diameter $d$, such that $\Gamma_t = \sqrt{2\nu/d}$ [6]. For the minimum probe beam waist in Fig. 2 of 18 μm, $\Gamma_t$ is approximately 17 MHz. Placing the vapor cell in the center between the fibers resulted in an EIT line that was too broad for RF E-field measurements. Instead, the vapor cell was placed such that the probe beam focus lies at the far edge, and the average beam size was closer to 100 μm. For room temperature $^{133}$Cs vapor and a probe beam diameter $d = 100$ μm, the transit-time-limited FWHM ($\Gamma_t$) is about 3 MHz, less than our minimum EIT linewidth. This setup resulted in a good trade-off between EIT signal strength and linewidth. Since the probe coupling into the return fiber was low (~22%), the probe intensity inside the vapor cell must be greater for the same amount of signal on the detector as in the free-space case. This caused additional power broadening of the EIT line. For our combination of probe and control powers...
inside the vapor cell, the measured linewidth of the fiber-coupled probe was 11 MHz, versus 6 MHz for our typical free-space EIT. While not ideal, this allowed us to perform RF E-field measurements using the fiber-coupled vapor cell down to just below ~1 V/m (compared with ~0.6 V/m for the free-space setup for the frequencies of interest in the next section).

3. FIBER-COUPLED VAPOR CELL MEASUREMENTS

The first measurements with our fiber-coupled vapor cell away from the optical table were set up as in the photograph in Fig. 3. The fiber-coupled cell was placed in front of a standard gain horn antenna. The RF E-field was measured with the fiber-coupled cell as the RF power input to the horn was varied (Fig. 4). The RF field was supplied by a signal generator feeding a horn antenna. Measurements were done at two different frequencies: 11.63 GHz and 9.22 GHz. Table 1 shows the atomic state combinations, dipole moments ($\mu$), and control laser wavelengths ($\lambda_c$) for the two frequencies measured.

<table>
<thead>
<tr>
<th>Cs Transition</th>
<th>RF Frequency (GHz)</th>
<th>$\lambda_c$ (nm)</th>
<th>$\varphi/ea_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$40D_{5/2}$ → $41P_{3/2}$</td>
<td>11.63</td>
<td>510.301</td>
<td>1025.1</td>
</tr>
<tr>
<td>$43D_{5/2}$ → $44P_{3/2}$</td>
<td>9.22</td>
<td>510.012</td>
<td>1195.7</td>
</tr>
</tbody>
</table>

The horn antenna was placed at a distance of 0.857 m ± 0.002 m (for RF = 11.63 GHz) and 0.843 m ± 0.002 m (for RF = 9.22 GHz) from the fiber-coupled probe. The probe and control laser powers inside the cell were 1.5 μW ± 0.1 μW and 8.20 mW ± 0.05 mW, respectively. For each frequency the RF power was swept and the optical frequency separation ($\Delta f$) between the AT peaks was measured. The E field was determined using Eq. (1). The fiber-coupled probe demonstrates the same linear relationship between the square root of the input power and the measured electric field as observed in the free-space measurements. The uncertainties in these measurements are ±5% as described in the section below.

We used the fiber-coupled probe to demonstrate other types of RF E-field measurements away from the optics table: a horn pattern measurement and an E-field pattern above a co-planar waveguide (CPW). We first show results for the horn pattern of a Narda 640 standard gain horn. (Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.) A horn pattern measurement is a typical method for characterizing RF horn antennas, which shows the spatial distribution of RF power emitted from the horn. This requires a large empty space where RF reflections are minimized so the pattern can be accurately measured. Without a fiber-coupled probe, it is very difficult to set up such a space near the optical bench. The horn antenna was fed with a 11.63 GHz frequency from a signal generator and oriented such that the E field was vertically polarized. The fiber-coupled probe was set at a distance of 0.857 m ± 0.002 m from the horn antenna, and the lasers were vertically polarized to match the horn. The E field was measured as a function of angle as the antenna was rotated in both the H-plane (azimuthal) and E-plane (vertical) directions. Figure 5 shows the relative power from the E-field measurements versus angle from on the axis. A comparison to a previous horn pattern measurement [18] (using a typical measurement method) is also shown. This test shows that the fiber-coupled probe is capable of determining the difference in the side lobe of the antenna pattern between the H plane and the E plane, as compared with the typical method (the difference in the shape can be attributed to the difference in frequency between the two sets of measurements).

We also used the fiber-coupled probe to measure the electric field pattern above a CPW, as shown in Fig. 6. We scanned the fiber-coupled probe across the CPW line (perpendicular to the center line) and measured the E-field profile at several different heights. The CPW line is a 208 mm × 50 mm copper surface on a substrate ($\varepsilon_r$ ≈ 3.5) of thickness 1.52 mm with a 3 mm width center line and 1 mm width gaps. The CPW was fed...
with an 11.63 GHz signal and terminated with a 50 Ω load. A dipole antenna cannot be used to measure this spatial distribution of the field at various heights, as placing a metal probe close to the CPW changes the field distribution. The all-dielectric fiber-coupled Rydberg atom-based probe allows for this sub-wavelength imaging.

4. UNCERTAINITIES

Understanding the uncertainties of this technique is an important step for this method to be accepted as a standard calibration technique. While we are working on an uncertainty budget for this measurement technique for the next-generation probe, below is an initial estimate for the uncertainties on the measurements in this work.

The uncertainties can be grouped into two categories: quantum-based uncertainties and RF-based uncertainties. The quantum-based uncertainties are dominated by the determination of the atomic dipole moment ($\mu$) and the linearity of Eq. (1). The dipole moments can be determined to be better than 0.1% [4]. The deviation from the linearity of Eq. (1) is controlled by the relative strength of the RF field compared to the strengths of the probe and control lasers [17]. By operating within a specified range, this uncertainty can be less than 0.5%. The quantum-based uncertainties for this work are negligible compared with the RF-based uncertainties.

The RF-based uncertainties are dominated by the standing wave created by the dielectric walls of the vapor cell. This is currently our largest source of uncertainty. There are several ways to mitigate this effect, including reducing the size of the vapor cell to be much smaller than the RF wavelength, simulating the effect of the vapor cell on the RF field, and mapping out the standing wave using the Rydberg atoms. An ideal solution would use all three strategies. For this work, we quantify the effect of the standing wave using the measured RF E-field amplitude at several locations in the vapor cell at different RF frequencies. Figure 7 shows the measured RF amplitude referenced to the mean field in the cell versus position in the cell along the direction of propagation of the RF field. This data was taken prior to attaching the fibers to the cell. After mapping the standing wave, the location of the fibers was fixed to be at 2.5 mm from the incident face of the vapor cell. At this location, the field is approximately 20% higher than average. This value can be used to correct for the standing wave effect. For a given frequency, the uncertainty due to the standing wave is

Fig. 5. Narda 640 standard gain horn pattern measurement with the fiber-coupled probe away from the optical table, compared with a previous measurement [18]. Error bars indicate ±5% uncertainty. Note that the previous measurement was done at a different frequency.

Fig. 6. Measurements of the electric field above a co-planar waveguide (CPW) line with an input RF = 11.626 GHz, at various heights. The data points are averages of several runs with the standard deviations as error bars. Photo from the top shows the dimensions of the CPW.

Fig. 7. Measurement of the RF standing wave inside the dielectric vapor cell. The normalized RF E-field amplitude is the ratio between the measured E-field and the average E-field. The position in the vapor cell is along the direction of propagation of the RF field (perpendicular to the laser propagation direction) and is referenced to the face of the vapor cell where the RF is incident.
about ±5%. We expect to reduce this number with further simulations and experimental data in future studies. Further information regarding the uncertainties of this technique are investigated in Refs. [1,2,4,17,19].

5. CONCLUSIONS

We have demonstrated an important step towards a fully portable Rydberg EIT-based RF E-field probe. While the laser generation and optical detection apparatus remain fixed to the optical table, the sensor head is now portable and can now be moved far away (>50 m from the optical table) to different measurement environments. The use of all-dielectric components reduces the perturbation of the RF E-field under test for a more accurate measurement. This allows us to use the Rydberg atom-based probe for measurements inside transverse electromagnetic (TEM) cells and anechoic chambers, giving us a direct comparison to existing RF field probes. Future probes can be improved by reducing the vapor cell size and the size of the stabilizing structure and optimizing the optical design for laser overlap within the cell and output coupling of the probe laser.

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