

Compact atomic vapor cells fabricated by laser-induced heating of hollow-core glass fibers

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A method for fabricating atomic vapor cells with physical dimensions of order 1 mm³ or below is described. Cells with integrated lenses are made from hollow-core glass fiber, and fused shut at either end using highly localized heating from a CO₂ laser beam. Such cells, subsequently loaded with alkali atoms and a buffer gas, could form the basis for future generations of compact frequency references or magnetometers. © 2003 American Institute of Physics. [DOI: 10.1063/1.1575925]

I. INTRODUCTION

A method for fabricating compact glass cells filled with an alkali atom vapor and buffer gas is outlined. Such cells may find application in highly miniaturized (volume < 1 cm³) atomic clocks¹ and magnetometers, which are currently receiving increased attention due to a range of both military² and civilian³ applications. Historically, the size reduction of physics packages for atomic frequency references using microwave cavities⁴ has been limited by the wavelength of the atomic ground-state hyperfine splitting. This is because of difficulties associated with making resonant cavities with dimensions significantly smaller than the resonant microwave wavelength in air, which is in the range of 3–21 cm for the atoms (¹³³Cs, ⁸⁵Rb, ⁸⁷Rb, and H) typically used for atomic frequency standards.

As a possible solution to this problem, designs of compact frequency references using all-optical excitation^{5,6} have recently gathered increased attention.¹ With this excitation method, no microwave fields are applied to the atoms directly. Instead, a laser field, modulated with an external oscillator at a subharmonic of the ground-state hyperfine frequency, excites a coherent population trapping (CPT)^{7,8} resonance in the atomic sample, which can be used to lock the external oscillator frequency to the atomic hyperfine transition. Atomic frequency references with physics package volumes as small as 14 cm³ have been built with this technique.⁹ The fabrication of ultrasmall vapor cells may well be the limiting factor for the miniaturization of atomic frequency references. Combined with miniaturized electronics, physics packages using all-optical excitation, and containing cells of small size, may lead to future generations of ultrasmall atomic frequency references.

Existing methods for cell fabrication rely heavily on traditional glass-blowing techniques. Typically, glass windows are attached to a piece of glass tubing using an optical con-

tact, chemical bonding, or alternatively a frit or other glass-blowing technique. A fill tube is attached to the cell tube wall and sealed with a torch after the cell has been filled with the alkali vapor and buffer gas. Cell fabrication using these methods becomes increasingly problematic at sizes below 1 cm due to the difficulty in locally heating one part of the cell with a conventional gas torch, while keeping other parts cool enough to maintain their structural integrity. While cells made from other materials such as metal¹⁰ or silicon¹¹ may prove useful, glass has the advantage of simple processing and reactivity with alkali atoms that is small and well understood. We describe here a method for fabricating small vapor cells out of hollow-core glass fibers. The hollow fibers are fused by use of light from a CO₂ laser, which allows for extremely localized heating of the glass. In addition, the beads formed in sealing the ends of the fiber make acceptable lenses for coupling light from a small source, such as a diode laser, into and out of the enclosed volume.

II. METHOD

The steps in a typical cell fabrication procedure are shown in Fig. 1. A piece of hollow-core Corning 7740 (Pyrex) glass fiber¹² of length ~5 cm, inside diameter 1 mm, and outside diameter 1.5 mm was rotated slowly about its axis to allow for uniform heating. Roughly 5 W of power from a CO₂ laser was focused somewhat beyond the tip of the fiber and was incident at an angle of about 45° with respect to the fiber axis. The beam diameter near the fiber tip was 3–5 times smaller than the diameter of the fiber; the laser beam was moved across the tip of the fiber throughout the heating process. Since light at the wavelength of the CO₂ laser (10.6 μm) is strongly absorbed by glass, the temperature of the fiber tip rose to near the softening point and the glass began to deform. Drawn towards the fiber axis by surface tension, the walls of the fiber near the tip eventually collapsed in on themselves and melted together, sealing the end of the fiber shut with a hemispherical bead of glass having a diameter roughly equal to the outer diameter of the fiber. The deformation and sealing typically occurred over a period of several tens of seconds, depending on the exact power level and strength of focusing of the laser. The lens

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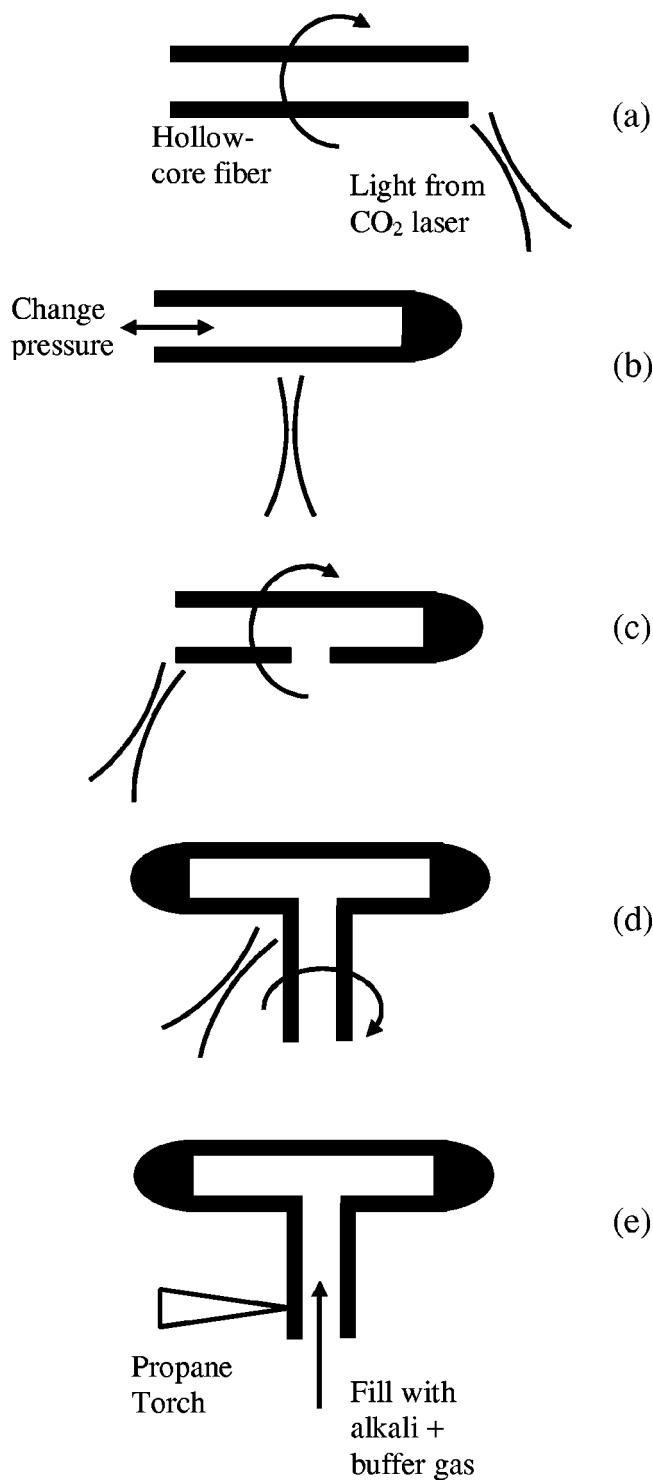


FIG. 1. Steps in the fabrication of small cells from hollow-core glass fibers: (a) one end of the fiber is fused shut with focused light from a CO₂ laser; (b) a hole is made in the fiber wall for attaching a fill tube; (c) the other end of the fiber is fused shut; (d) a fill tube is attached; and (e) after filling, the fill tube is sealed shut.

formation and final quality were very tolerant to the optical and alignment conditions provided the power was not too high (<5 W) and the focusing was not too sharp. The reliability of this step was high since the deformation of the glass occurs as a result of surface tension. While the number of bubbles and the length of the cusp-shaped void varied slightly with heating conditions, the quality of lens surface

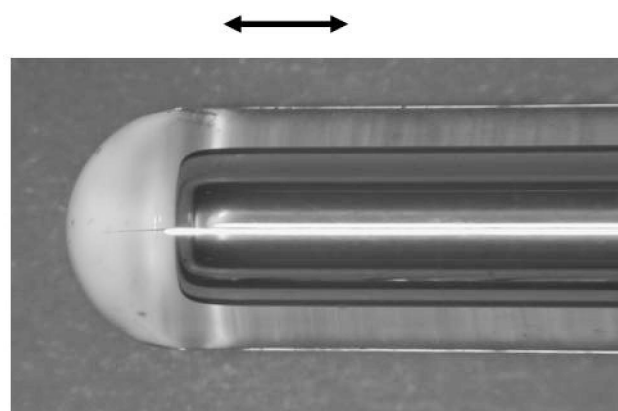


FIG. 2. The end of a Pyrex fiber sealed using light from a CO₂ laser. The arrow indicates a distance of 1 mm.

was consistently high. A similar melting technique has been used to form glass microcavities of extremely high *Q* factor.¹³ A photograph of a typical sealed fiber end is shown in Fig. 2. Although our studies concentrated on Pyrex, tests with fused-silica tubing also gave promising results.

The correct power level is important for avoiding two common problems associated with the seals. If the power is too low, a sort of hollow cusp can form within the hemispherical glass bead (also shown in Fig. 2), which can prevent the seal from being airtight. If the power is too high, gas bubbles can form inside the bead. These bubbles scatter light passing through the glass and reduce the effectiveness of the bead as a lens for coupling light into the enclosed volume. To avoid creating bubbles, the laser intensity was reduced and the heating time lengthened. The optimum laser intensity was found to be roughly 10 kW/cm².

This sealing method can be used in the following way to make vapor cells. After sealing one end of the fiber, a hole is made in the wall of the fiber 1–2 mm from the sealed end, in order to attach a filling tube [see Fig. 1(b)]. To do this, the laser beam is focused onto the wall of the (nonrotating) fiber and the pressure inside the fiber is changed through a rubber tube attached to the open end. Roughly 10 W of laser power is focused to a diameter of ~0.5 mm on the wall of the tube, which softens the glass at that location. The fiber's internal pressure is then cycled from above to below atmospheric pressure, thinning the glass in the vicinity of the laser spot; eventually a hole with an outward-protruding edge is created in the fiber wall with a final strong increase of internal pressure. This hole typically has a diameter of 0.4–0.8 mm, large enough to allow the attachment of a fill tube. Holes can also be made without changing the internal pressure of the fiber (if the process needed to be carried out in a vacuum, for example) by focusing the laser beam more tightly (to a diameter of ~0.1 mm).

Next, the fiber is cut to the desired length (usually 5–6 mm) and the other end of the fiber is sealed in the same manner as the first [Fig. 1(c)], creating a cell preform, sealed at both ends with lens-like glass beads, and with a hole in the side wall to allow for the attachment of a filling tube. The filling tube was attached [see Fig. 1(d)] by placing a second hollow-core fiber perpendicular to the first, with the hole at the end of the second fiber coincident with the hole in the



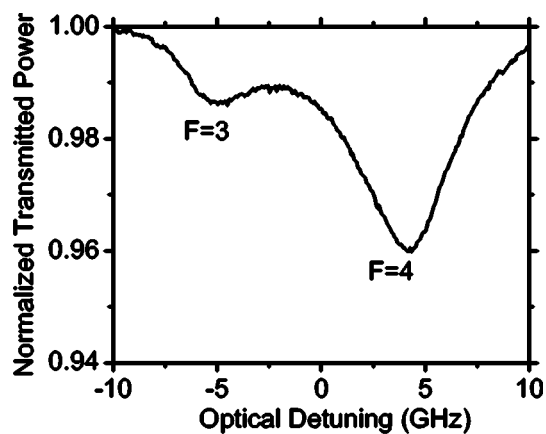
FIG. 3. A cell fabricated from a hollow-core Pyrex fiber using CO₂ laser fusion. The arrow indicates a distance of 1 mm.

side wall of the first. The two fibers were then fused together by heating the junction between the fibers with CO₂ laser light while rotating the two pieces together at the same rate about the axis of the filling tube [Fig. 1(d)]. The seal was facilitated by controlling the gas pressure through a rubber blow tube attached to the side tube. The reliability of this last operation was good when the diameter of the outward-protruding edge of the hole in the first fiber was close to the inner diameter of the filling tube. Once the filling tube was pushed against the conical protrusion around the hole in the first tube and the end of the filling tube was heated, surface tension constricted the edge of the tube and it fused easily to the edge of the hole. Again, the deformation of the glass caused by surface tension was quite predictable and the sealing process worked reliably for several connections we attempted. The shape and quality of the T connection could also be improved after the initial seal by local heating with the CO₂ laser combined with simultaneous variation of the pressure inside the cell with the blow tube.

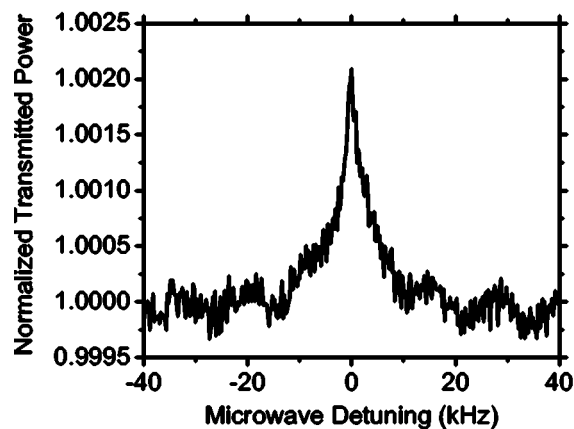
The filling tube was then attached to a conventional cell-filling manifold and Cs metal was distilled into the cell, before backfilling with Ne to an appropriate pressure as measured with a capacitance manometer. Finally, the filling tube was sealed using a micropropane torch (although a CO₂ laser could also be used), creating a cell [Fig. 1(e)]. A photograph of a cell fabricated in this manner is shown in Fig. 3. The Ne pressure in the final, cool cell was estimated to be ~ 18 kPa by a measurement of the pressure-induced frequency shift of the Cs hyperfine resonance.

III. RESULTS

To determine that the cell was indeed sealed, and also to demonstrate the utility of such a compact cell in applications



(a)



(b)

FIG. 4. (a) A Cs optical absorption spectrum measured in the small cell and (b) a dark-line CPT resonance. In both cases, the resonance is normalized to the off-resonant intensity.

to atomic frequency references, some simple spectroscopy was carried out. A diode laser was tuned to the D₂ transition in Cs at 852 nm and the frequency swept over the optical transition. A two-peaked resonance indicating the two hyperfine absorption components separated by 9.2 GHz is shown in Fig. 4(a), and indicates the presence of Cs vapor in the cell. The large width of these transitions is a result of collisional broadening due to the Ne buffer gas. Finally, the cell was placed in a magnetic shield and heated to $\sim 60^\circ\text{C}$. A dark-line CPT resonance was excited by modulating the diode laser injection current at the first subharmonic (near 4.6 GHz) of the hyperfine splitting. The transmitted intensity as the microwave modulation frequency was scanned over the hyperfine transition is shown in Fig. 4(b). While the CPT resonance is fairly broad (5 kHz), it was possible to use it to stabilize an external quartz crystal oscillator and synthesizer; a fractional frequency instability of 5.5×10^{-10} was obtained at an integration time of 1 s.

The 5 kHz wide CPT resonance measured in this cell was substantially power broadened by the optical field. The width extrapolated to zero power was ~ 1 kHz. This intrinsic

resonance width is substantially larger than widths obtained in larger (> 1 cm) cells, which can be below 100 Hz, primarily because collisions of the atoms with the cell walls occur more often in the smaller cell. However, the width is consistent with theoretical predictions based on the diffusion of atoms in the buffer gas.^{1,14} We expect a reduction in the linewidth could be obtained by further optimizing the buffer gas pressure in the cell or through the use of a wall coating such as paraffin.

IV. DISCUSSION AND OUTLOOK

Other related fabrication processes based on the CO₂ sealing procedure outlined above appear feasible. Drawbacks of having to attach a filling tube, for example, are the added complexity (two tubes, rather than one), larger size, and the difficulty in fabricating more than one cell at a time. It is possible, however, to place a fiber with one sealed end inside a vacuum system, and then to deposit alkali metal into the cell from an atomic beam (or vapor). The cell could then be backfilled with an appropriate buffer gas pressure and the open end sealed inside the vacuum system, again with a CO₂ laser. Multiple cells could in fact be placed in the vacuum system, filled simultaneously with an atomic beam, and then sealed shut sequentially simply by changing the location of the focus of the laser beam. Multiple cells could also be fabricated from a single larger piece of tubing.

It also appears likely that this general fabrication method could be used to make cells with dimensions substantially smaller than 1 mm. Hollow-core fibers are available with interior diameters as small as 10 μ m. It is likely that at these small scales, the limit to the size of the cell that could be fabricated would be determined either by the thermal conductivity of the glass or by the minimum achievable beam waist of the CO₂ laser.

We have demonstrated a method for fabricating atomic vapor cells with dimensions of the order of 1 mm, using highly localized heating with a remote source. The cells are made from hollow-core Pyrex fiber, sealed using light from a CO₂ laser. This sealing mechanism provides for the highly

localized deposition of energy into the glass, allowing small-scale structures to be made with a high degree of control over the heating parameters. In addition, this new method allows for glasswork to be carried out in a vacuum or other environment unsuitable for a flame. Cells made in this manner and filled with a vapor of alkali atoms and a buffer gas are suitable for use in ultrasmall devices based on atomic vapor cells. Such small cells may become increasingly important as size reduction for atomic clocks and magnetometers gains momentum and as applications for such devices become apparent.

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¹²Specific product is named only for technical clarity and does not constitute or imply endorsement by NIST. Other products may be found just as well suited to this application.

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