3D printed microwave cavity for atomic clock applications: proof of concept

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The authors present the realisation and characterisation of an additively manufactured (AM) microwave resonator cavity for double-resonance (DR) vapour-cell atomic clocks. The design of the compact microwave cavity is based on the loop-gap resonator approach, previously demonstrated for conventionally-machined aluminium components. In the present study, the resonator is fabricated by AM using a metal-coated polymer. A resonance frequency at the desired 6.835 GHz rubidium atomic frequency is obtained. When employed in an atomic clock setup, the AM cavity enables a DR signal of <500 Hz linewidth and of nearly 20% contrast, thus fulfilling the stringent requirements for DR atomic clocks. A clock short-term stability of $1 \times 10^{-12}\ \tau^{-1/2}$ is demonstrated, comparable to state-of-the-art clock performances.

Introduction: Additive manufacturing (AM) technologies [1], such as selective laser melting, stereolithography (SLA) or 3D printing, have revolutionised the fabrication approach for a multitude of applications, enabling the realisation of complex components hardly achievable using standard machining techniques. Apart from this advantage, it also enables significantly reduced component mass, lower cost, and shorter lead-time. In the field of microwave components and antennas, AM has already proven its efficiency for components such as waveguides or antennas [2, 3], and basic cylindrical cryogenic microwave cavities manufactured by selective laser melting of aluminium have been demonstrated [4].

A large majority of commercially available atomic clocks, widely used in telecommunication networks, satellite navigation systems, avionics and time references, require the use of a microwave cavity (e.g. atomic fountain clocks, hydrogen maser, Rb-cell clocks, Cs beam standards) [5]. Continuous-wave double-resonance (CW-DR) is a well-established technique for the realisation of atomic clocks, currently covering most of the market on telecommunications and satellite applications, for which timing performance as well as size, weight, and power consumption are essential. The heart of CW-DR atomic clocks consists of a Rb vapour-cell and microwave-resonator assembly, which serves as an extremely stable frequency discriminator for stabilising the frequency of a quartz oscillator. The achievements, in terms of volume and stability, of high performance atomic clock, have been continuously improved over the last few decades. Recently, state-of-the-art short-term clock stabilities at the level of $1.4 \times 10^{-13}\tau^{-1/2}$ have been demonstrated from a 1 dm^3 physics package, using a magnetron-type microwave cavity, realised by classical bulk machining of aluminium, and employing a laser instead of a discharge lamp for the optical pumping and detection (see below) [6, 7]. Apart from the stability performance of the clock, manufacturing cost and instrument weight are crucial parameters for atomic clocks, particularly for space applications. AM technology based on metal-coated polymers instead of bulk-machined aluminium is thus of high interest for many types of atomic clocks, thanks to the significant reduction in weight of the physics package, as well as cheaper and faster manufacture of complex cavity geometries.

Continuous-wave atomic clocks: The principle of a CW-DR atomic clock is based on the simultaneous and continuous interaction of a population of atoms with two, respectively, optical and microwave, resonant fields. The light (generally at 780 nm for a Rb atomic clock) serves both for the preparation and read-out of the Rb ground state ($^5S_{1/2}$) populations. When the microwave field is applied at the atomic resonance frequency (≈6.835 GHz), it will counter-act the population inversion generated by the optical field, reducing the optical transmission of the atomic vapour. The Rb 'clock' transition $|F_g = 1; m_F = 0\rangle \leftrightarrow |F_g = 2; m_F = 0\rangle$, is only weakly sensitive to magnetic fields. A static magnetic field (named hereafter the C-field) is applied that lifts the degeneracy of the hyperfine ground state levels and also defines the quantisation axis. The selection rules applying to the atomic transitions involved impose severe restrictions for the relative orientations of the electromagnetic fields (see Fig. 1). Indeed, the magnetic component of the microwave field must be parallel to the C-field (generated by a coil wound around the cavity) in order to interrogate the desired clock transition. The requirements of the microwave cavity are to sustain such a microwave field of well-defined geometry, hold the cell that contains the atomic vapour to be interrogated, and allow the light to pass through. A typical interrogation geometry for a vapour-cell atomic clock is shown in Fig. 1.

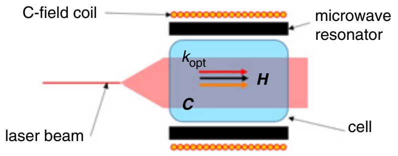

Fig. 1 *Schematic representation of fields' orientations required for CW-DR atomic clock.* ***k****, light propagation vector;* ***H****, microwave magnetic field;* ***C****, static magnetic field*

Cavity design: In our case, the microwave cavity is based on a loop-gap geometry (Fig. 2) developed previously and realised in aluminium using traditional machining means [8]. This kind of geometry is significantly more compact than the typically used cylindrical cavities and at the same time are characterised by excellent performance in terms of field homogeneity as well as high uniformity of the field orientation (Fig. 2*a*), defined as field orientation factor (FOF): FOF ≈ 90% [8]. The cavity properties and resonance frequency critically depend on the electrode geometry and the gaps between them, which requires high precision for machining and assembling the seven traditionally-machined aluminium parts. This can be circumvented by the monolithic manufacture of the entire cylinder and electrode geometry (Fig. 2*b*).

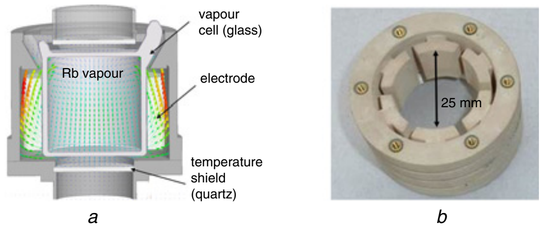

Fig. 2 *Details of cavity*

a Cavity model with simulated magnetic field. The cavity consists of a cylindrical structure loaded with six metallic electrodes separated by air gaps. The gap distance between the electrodes can be used to tune the TE$_{011}$-like mode to the required ≈6.835 GHz. The magnetic field in the central region is oriented almost entirely along the central symmetry axis of the cavity
b Monolithic cavity cylinder with electrodes fabricated by AM. The polymer body is copper plated and passivated by silver; metallic inserts are added for fixing the cavity top and bottom parts

Cavity fabrication: The cavity cylinder with electrodes was fabricated by SWISSto12 SA using SLA, an AM process in which a liquid polymer is selectively cured, layer by layer, by light-activated polymerisation (laser) [1]. The local manufacturing precision is mainly driven by the laser spot size (resolution), which is nowadays around 40 μm. Such a precision enables high-performance microwave devices even at 30 GHz [3, 9] and is considered sufficient for this application (the residual small frequency shift, dominated by the vapour cell dimensional uncertainty, is compensated by a tuning mechanism incorporated in the cavity). The density of the material used is 1.65 g/cm^3 (about 61% of the density of aluminium), thereby bringing significant mass savings with respect to classical fabrications. The material properties do not vary significantly with aging when it is used in a stabilised environment typical for atomic clocks of this type. The polymer body was then metal plated, using a proprietary electroless plating process, to become RF-functional. The resulting copper layer is homogeneous and of sufficient thickness (at least seven skin-depths) on all surfaces of the polymer body. Finally, metallic surfaces were passivated by a thin silver finish.

Experimental validation: The S_{11} parameter of the AM microwave cavity was measured and compared with simulation results, see Fig. 3. A resonance frequency for the desired TE$_{011}$-like mode was found at the ≈6.835 GHz Rb atomic frequency, in agreement with simulations. The moderate loaded Q-factor measured (≈60) is attributed mostly to dielectric losses from the vapour cell walls and is desirable for avoiding clock instabilities due to cavity pulling [5]. Fig. 4 shows the DR signal obtained with the AM cavity operated in a Rb atomic clock setup. The excellent field properties of the cavity allow detection of a clean, narrow, and high-contrast atomic signal. The full width at half maximum (FWHM) of the Lorentzian DR signal is <500 Hz, with a contrast (signal amplitude over background) of nearly 20%. We estimate the expected short-term clock stability (Allan deviation [10]) as [11]

$$\sigma_y(\tau) = \frac{N}{\sqrt{2} \cdot \nu_0 \cdot D} \tau^{-1/2}, \tag{1}$$

where N is the measured detection noise power spectral density, D is the slope of the discriminator signal (see Fig. 4*a*), and ν_0 is the frequency of the clock transition. From (1), and the measured detection noise, we predict a short-term clock stability of $1.1 \times 10^{-12}\ \tau^{-1/2}$, and a shot-noise limit of $1.3 \times 10^{-13}\ \tau^{-1/2}$. The measured clock stability of $1.12 \times 10^{-12}\ \tau^{-1/2}$ (Fig. 4*b*) is in good agreement with the predicted value and clearly demonstrates the correct operation of the AM microwave cavity. By optimising the detection scheme, we expect to obtain a discriminator slope of $D = 2.4$ A/FWHM, with A the amplitude of the dc Lorentzian signal, and thus a predicted optimised short-term clock stability of $4 \times 10^{-13}\ \tau^{-1/2}$, comparable to state-of-the art vapour-cell atomic clock stabilities [7, 12].

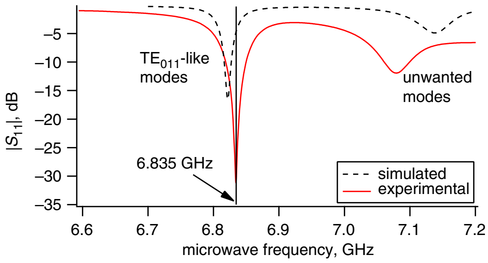

Fig. 3 *Microwave cavity resonance: simulation versus experiment, shown for the $|S_{11}|$ parameter. Additional fine-tuning was considered for the experimental case. Increased coupling of the unwanted mode is attributed to manufacturing tolerances of the vapour cell*

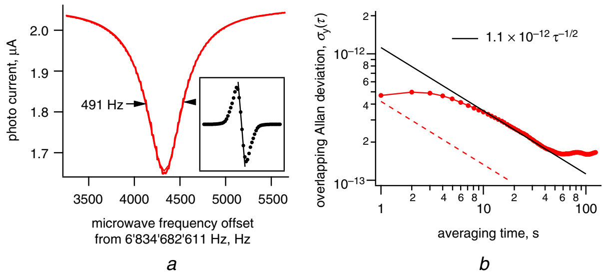

Fig. 4 *Clock experimental results*

a Double resonance clock signal (data and Lorentzian fit) with amplitude $A = 0.4$ μA. Inset: lock-in error signal with discriminator slope of $D = 0.61$ nA/Hz
b Measured clock short-term stability (red dots) versus predicted optimised stability (red dashed line)

Conclusions: We have designed, manufactured, and characterised the prototype of a compact microwave cavity based on the AM of polymers. The proof-of-principle clock stabilities obtained and predicted are in excellent agreement with previous studies using conventional machining techniques. In view of future applications to atomic clocks, it would be of interest to study the performance of the realised microwave cavity for pulsed optically pumped interrogation [12, 13], as well as the long-term aging behaviour of AM polymer microwave structures.

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One or more of the Figures in this Letter are available in colour online.

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