Maser Oscillation in a Whispering-Gallery-Mode Microwave Resonator

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We report the first observation of above-threshold maser oscillation in a whispering-gallery(WG)-mode resonator, whose quasi-transverse-magnetic, 17th-azimuthal-order WG mode, at a frequency of approx. 12.038 GHz, with a loaded $Q$ of several hundred million, is supported on a cylinder of mono-crystalline sapphire. An electron spin resonance (ESR) associated with Fe$^{3+}$ ions, that are substitutively included within the sapphire at a concentration of a few parts per billion, coincides in frequency with that of the (considerably narrower) WG mode. By applying a c.w. ‘pump’ to the resonator at a frequency of approx. 31.34 GHz, with no applied d.c. magnetic field, the WG (‘signal’) mode is energized through a three-level maser scheme. Preliminary measurements demonstrate a frequency stability (Allan deviation) of a few times $10^{-14}$ for sampling intervals up to 100 s.

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Short-term ($<100$ s) fractional frequency stabilities better than $1 \times 10^{-14}$ have only ever been achieved at microwave frequencies with oscillators incorporating cryogenic ($<10$ K) electromagnetic resonators exhibiting $Q$ values in excess of 100 million. Such oscillators have been used successfully as ‘flywheels’ for cold-atom frequency standards, and in tests of fundamental physics (e.g. Lorentz invariance).

Two decades or so ago, Dick et al developed a ‘superconducting cavity maser oscillator’ (SCMO). It incorporated a cryogenic maser amplifier whose ruby crystal was necessarily subjected to a d.c. magnetic ‘bias’ field. This amplifier was intentionally separated from, yet electromagnetically coupled to, a high-$Q$ resonator through an intermediate waveguide structure. The resonator took the form of a lead-coated sapphire cylinder, maintained at a temperature near 1.6 K.

In recent years, the most actively studied resonators have been those based on whispering-gallery (WG) modes, supported on uncoated sapphire cylinders or rings that are immediately surrounded by free space, where the cylinder’s diameter-to-height ratio is greater than unity, and where the resonator is generally maintained at a temperature above 4.2 K. Here, the bulk of the WG mode’s field energy resides just within the curved outer cylindrical wall of the sapphire monocrystal. A Pound-stabilized-loop oscillator (PSLO) is built around the WG-mode resonator, with the oscillator’s sustaining amplifier and phase modulator(s) located outside of the cryostat. A PSLO is thus a spatially extended system; two microwave lines, each typically $>1$ m in length, join the cryogenic resonator and room-temperature electronics together in a loop. Moreover, to achieve stabilities at the $1 \times 10^{-14}$ level, additional circuits supporting the control of the resonator’s temperature and received microwave power are required.

In all of the oscillators so far described, the electromagnetic resonator functions as a purely passive, linear device (except potentially for a slight power-dependent frequency shift). In contrast, we report here the observation of continuous, above-threshold maser oscillation in an active resonator. Here, amplification is achieved through the interaction between a whispering-gallery mode and a collection of ($\sim 10^{15}$) paramagnetic ions that exhibit an electron spin resonance (ESR). These ions are located, in space, within the WG mode’s field profile and the WG mode is located, in frequency, within the ESR’s lineshape. Compared to Pound-stabilized loop oscillators, or even Dick et al’s SCMO, our incorporation of maser gain within the oscillator’s frequency-determining element represents a fundamentally different approach.

Our whispering-gallery(-mode) maser oscillator, henceforth ‘WGMO’, may be regarded as a free-running loop oscillator, whose loop is the (closed) path taken by its WG (signal) mode through space, and whose amplifier is continuously distributed around this loop. Some immediately apparent advantages are: (i) the rigidity and compactness of the all-sapphire oscillator loop enables its electromagnetic length (hence the WGMO’s frequency –as determined by the Barkhausen condition) to be kept extremely constant; (ii) unlike a ruby maser, no d.c. magnetic bias field need be applied; (iii) compared to a PSLO or even the SCMO, the WGMO comprises fewer essential components, viz. just the sapphire cylinder and its associated electromagnetic

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pump- and signal-mode couplers; there is no Pound frequency servo; there are no cables or coupling structures between a spatially separated amplifier and resonator; (iv) moreover, the adjustment of the electromagnetic couplings to the maser oscillator’s signal and pump modes are, in contrast to the equivalent adjustments required for optimizing a PSLO, far less critical.

FIG. 1: Principle of the Fe$^{3+}$ WG-mode maser oscillator.

Half a century or so ago, the study of electron spin resonance in solids led to the development of solid-state masers [12, 13] as sufficiently wideband, extremely low-noise amplifiers for applications in satellite communications and radio astronomy. Sapphire crystals deliberately doped with Fe$^{3+}$ ions, as opposed to Cr$^{3+}$, were studied by a few groups [14, 15]; even a few maser amplifiers based on the former species were demonstrated [16, 17].

Our electromagnetic resonator (see fig. 1) contains a monocrystal of HEMEX-grade sapphire that comprises a main cylinder, 50 mm in diameter and 30 mm high, with a smaller, coaxially adjoining cylinder (its ‘spindle’) for support; this monocrystal is mounted coaxially within a cylindrical copper cavity, whose interior walls are silver-plated. The monocrystal can support various whispering-gallery modes but only two of them, both quasi-transverse-magnetic (WG) in character, are presently relevant: (i) a fundamental (i.e. with no axial or radial nodes) 17th-azimuthal-order WG mode, at approx. 12.038 GHz and (ii) a different, as yet unidentified WG mode of considerably higher azimuthal-order at approx. 31.339 GHz. [Both of these frequencies refer to near-4.2 K operation.] These two WG modes shall henceforth be referred to as the ‘signal’ and ‘pump’ modes, respectively. The former is excited by an appropriately positioned and oriented loop probe (sensitive to the magnetic field’s azimuthal component), the latter by a stub antenna (sensitive to the electric field’s axial component).

The latter was excited, via its corresponding transmission line with terminating stub antenna, by the (c.w.) output of an Agilent E8254A microwave frequency synthesizer. When this pump synthesizer was set to a frequency of 31.339 GHz, and an output power level of 2 dBm, a −56 dBm signal at approx 12.038135 GHz on the other transmission line, as connected to the resonator’s loop probe, could be detected at the insert’s top plate (see fig. 2(b)). This signal, caused by maser oscillation on the $W G H_{17,0,0}$ signal mode, was amplified by 70 dB then mixed (with a doubly balanced mixer) against the signal from a second microwave synthesizer (Wiltron 69137A) referenced to a commercial hydrogen maser. The resulting beat-note (approx. 91 kHz in fre-
frequency) was sent to a high-resolution frequency counter (HP 53132A). By slowly increasing the resonator’s temperature whilst monitoring this counter, we observed the WGMO’s signal frequency to turn over (a maximum) at a temperature of approx. 7.939 K. The resonator’s temperature was then stabilized at this turn-over and the beat-note frequency measured against time. The corresponding fractional-frequency Allan deviation was subsequently computed, with the result shown in fig. 3.

![FIG. 3: Frequency stability of WGMO; the dashed line indicates the stability of the measurement’s frequency reference.](image)

The stability of the reference synthesizer limited the measurement’s resolution for sampling intervals $\tau < 20$ s. Nevertheless, a minimum in the Allan deviation of $2.5 \times 10^{-14}$ at 40 s was obtained.

We point out that the RG-405/SMA-based transmission line for conveying the Ka-band pump down through the insert was not designed or tested for operation above 18 GHz. For lack of appropriate equipment, the power reflected back from the pump probe, hence the coupling to the pump mode, could not be quantified. Assuming a spin-lattice relaxation time ($T_1$) of a few ms, the measured $-56$ dBm level of maser signal power is consistent with the parts-per-billion concentration of Fe$^{3+}$ ions inferred from our other measurements (mentioned above) on the same sapphire monocrystal; the $|1/2\rangle \leftrightarrow |5/2\rangle$ transition was not fully saturated at the 2 dBm level of applied pump power used.

The origin of the long-term degradation in the frequency stability has yet to be determined. No microwave isolators (for either X-band or Ka-band) were placed in the transmission lines between the resonator and the top plate within the insert; shifts in the VSWRs in sections of these lines (caused by changes in the cryostat’s temperature profile due to boil-off of liquid helium) could thus have significantly ‘pulled’ the maser oscillator’s frequency. We now plan to evaluate the WGMO’s sensitivities to pertinent experimental variables including the pump power and frequency, the signal- and pump-mode couplings, the loading and VSWR along of the pump and signal transmission lines, as well as the ambient and/or a deliberately applied magnetic field.

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