CPT MASER CLOCK EVALUATION FOR GALILEO

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Abstract

The possibility of using the Coherent Population Trapping (CPT) mechanism for the implementation of atomic frequency standards was proposed in the last decade, and experimental work is currently being carried on in various laboratories.

The Istituto Elettrotecnico Nazionale (IEN) "G. Ferraris," with the support of Alenia Spazio, is currently developing under an ESA contract, a Rb CPT maser frequency standard prototype (breadboard), with the aim to evaluate its ultimate stability capabilities in the range from 1 s to 1 day.

The expected short-term stability is 10^{-12} $\tau^{-1/2}$, with a flicker floor of 10^{-14}.

This stability performance, if achieved, would be of great interest for the Galileo satellite navigation system, lying between the stability performances of a traditional lamp-pumped rubidium and that of a passive H-maser with a significant reduction of complexity.

PROJECT GOAL

While looking at possible clock implementations suitable for space applications, the CPT maser technology is rather new, and it has not yet completely investigated to understand its ultimate performance in the clock realization.

Up to now the only extensive study of this technology has been performed at the IEN Time and Frequency Laboratories **[1]**, while other laboratories worldwide have investigated in more details a different technique (called the *dark line* **[2]** technique). Despite the two excitation techniques have many similarities, the differences between the two frequency standards are quite significant. In the following some of the differences between the two techniques will be pointed out.

Until today, the experiment carried out in the IEN laboratories were mainly focused to the study the physical mechanism underlying the CPT maser phenomenon (a phenomenon discovered in 1998 for the first time **[3]**). Since then extensive experiments were carried out in order to understand the CPT maser behavior in depth, but always with particular attention to possible application in the time and frequency metrology. Some preliminary results have shown a promising behavior, especially with respect to the short-term stability.

The current project is finalized to the investigation of the ultimate performance of a CPT rubidium maser frequency standard regarding its frequency stability from 1 s to 1 day. The prototype will be integrated only at the level required to establish the clock performances, and commercial components will be used where necessary. In particular, while we will try to minimize the volume, the optical bench will be implemented with commercial parts, and no integration of the optical elements is planned at this stage.

Demonstration of the best frequency stability achievable (the specification calls for a few parts in $10^{-12}\ \tau^{-1/2}$) is therefore the main goal of the current project.

BRIEF THEORETICAL DESCRIPTION OF THE CPT MASER

The operation of atomic frequency standards using alkali atoms involves three steps: state preparation, atomic coherent excitation, and detection. The state preparation is done by populating one hyperfine level at the expense of the other. In the case of hydrogen maser or optically pumped Rb masers, the upper level is more populated than the lower one. Energy is stored in the ensemble of atoms, and when this ensemble is placed in a microwave cavity tuned to the resonant frequency of the atoms, a self-sustained atomic oscillation takes place through the phenomenon of stimulated emission.

Efforts have been spent on the implementation of schemes for inverting populations. Intensity optical pumping is used in the rubidium optically pumped maser, while spatial state selection by means of an inhomogeneous magnetic field is used in the hydrogen maser.

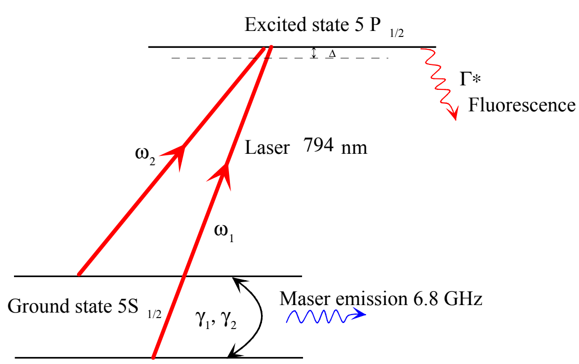

Figure 1. Lambda diagram.

In the case of cesium, intensity optical pumping can be accomplished by means of lasers, but the implementation of a cesium maser has been inhibited by the fact that a simple sufficiently high Q cavity could not be constructed.

The phenomenon of coherent population trapping (CPT) provides a new approach in addressing these problems, and several suggestions have been made concerning its use in the implementation of atomic frequency standards.

The CPT exploits the coherent property of laser radiation to combine both the state preparation and the microwave excitation of the ensemble in a single step. Two coherent laser radiations are used to couple the two hyperfine ground levels to a common excited state, in occurrence the P state (Figure 1).

If the laser frequency separation is equal to the ground state hyperfine frequency, the two optical excitations interfere. No intensity optical pumping takes place, as in the classical approach, and the population of both ground state hyperfine levels remain unaltered.

In this condition the atomic ensemble is driven by the laser beams in a coherent state that has some peculiar properties well suited for the implementation of an atomic frequency standard. If the coherent ensemble is placed inside a resonant microwave cavity, a maser emission is stimulated (without a threshold) at the laser frequency difference. If otherwise the light spectrum is observed in fluorescence, a dark line appears when the two laser frequency difference match the hyperfine frequency ground state splitting; while in the light transmitted a bright *electromagnetic induced transparency* (EIT) effect is observed. Either of the above-described effects can be used to realize a novel atomic frequency standard; in fact, all of them are maximized when the laser difference equals the hyperfine frequency splitting of the ground state, allowing one to close the microwave loop on the atomic transition.

In a practical implementation, the ^{87}Rb D_1 line is chosen and the two ground states $5S_{1/2}$, F=1 and $5S_{1/2}$, F=2 are connected to the excited $5P_{1/2}$ state, through two laser beams at frequencies ω_1 and ω_2. When the atomic ensemble is contained in a glass cell, a buffer gas may be used to inhibit Doppler broadening of the hyperfine resonance line and relaxation on the walls of the containing cell, as in the case of the technique using intensity optical pumping. The huge line broadening of the excited state due to the presence of the buffer gas (700 MHz) allows one to discard the excited state hyperfine structure. To preserve the coherence of the system, the two laser beams are generated by phase modulation of a single laser carrier lying at the center of gravity of the D_1 lines.

The use of the CPT rubidium maser signal to realize a clock can in principle provide a quite good atomic reference oscillator exhibiting very good short- and medium-term stability in a compact and relatively simple device.

Both phenomena, the dark line and coherent microwave emission, can be used as the basis of the implementation of a practical novel atomic frequency standard. However, despite the more complex physical setup of the maser that requires a microwave cavity and a heterodyne detection system, the fact that the signal is not detected as an absorption signal allows one to reduce the noise conversion, and to further increase the atomic density of the medium. This leads to higher S/N ratios and, therefore, we expect a better stability. Another important feature unique of the CPT phenomena is the line-width reduction with increasing atomic density. These phenomena can be even more important in the maser approach, because here it is possible to allow for an even stronger attenuation of the laser beam along the path inside the absorption cell.

CPT MASER EXPERIMENTAL STATUS

Three subsystems comprise the current device configuration:

1. Optical subsystem (laser, electro-optic modulator, fiber couplers, polarization optics);
2. Physical package (microwave cavity, absorption cell, C-field, heater, magnetic shields);
3. Electronic package (heterodyne detection, synthesis chain, and frequency loops).

OPTICAL SUBSYSTEM

The laser source is a monolithic external cavity commercial laser diode[1] composed of two parts, the laser head and the power supply (including temperature control, laser cavity tuning, and current generator). It is fiber-coupled into a broad band E-O modulator[2], which generates the two optical radiations required for the CPT excitation process. The system (Figure 2) has shown to be very stable and reliable also for long-term measurements, and does not need much of improvement from the mechanical and optical point of view; clearly a more compact setup will be useful and can be obtained also with miniaturized commercial components.

Despite the strong reduction of the FM/FM noise transfer from the laser to the microwave signal, if compared to the optically pumped Rb frequency standard, to obtain a stability in the 10^{-14} range a suitable laser frequency servo-loop must be developed; the laser stability required is around 10^{-11}: it is

[1] New-focus vortex laser
[2] Alenia Marconi Systems

therefore necessary to lock the laser central frequency to a saturated absorption signal (Doppler-free), because the signal obtainable from the buffer gas cell used also for the maser emission is not good enough. With respect to the present experimental status, major improvement can be obtained rebuilding the frequency servo-system of the laser.

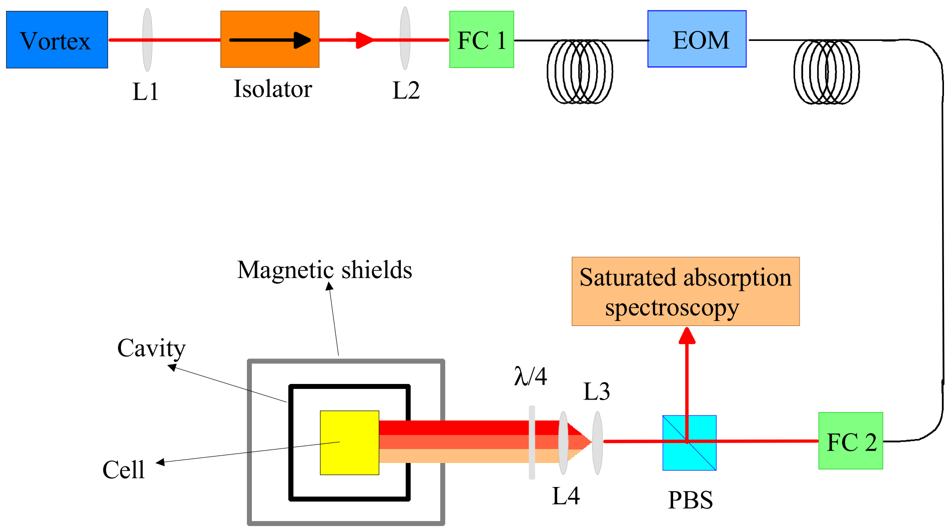

Figure 2. The optical setup.

Physical Package

A new physical package (including microwave cavity, ^{87}Rb cell, C-field, heater, and magnetic shields) is being developed in order to reduce volume and weight. The ^{87}Rb cell will be constructed with quartz in order not to degrade the cavity Q, and will be filled with the appropriate mixture of buffer gas to reduce the temperature sensitivity. The microwave cavity is designed to be resonant at the right temperature with the quartz cell inserted inside, with a limited degree of tuning.

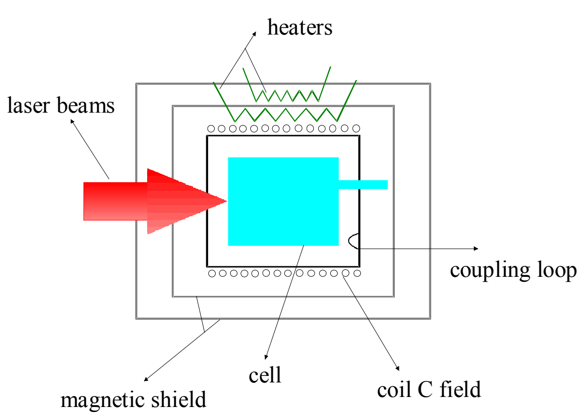

Figure 3. Microwave cavity.

Electronics

The electronics consists of the following subsystems:

1. Microwave synthesis chain (from 10 MHz to 3.4 GHz);
2. Heterodyne detector and VCXO frequency control loop;
3. Temperature and magnetic field servo systems;
4. Laser frequency stabilization loop.

A 10 MHz low-phase noise Oven-Controlled Crystal Oscillator (OCXO) is the local reference microwave synthesis chain (Figure 4). The OCXO features a short-term stability of parts in 10^{-12} to comply with the short-term stability required by the standard. A control port allows frequency control of the oscillator over a range suitable for accommodating a lifetime of 10 years while, at the same time, keeping the control range as narrow as possible to minimize the frequency instability effects resulting from amplitude noise on the control signal. The output signal from the oscillator is split to provide multiple outputs using an active buffer/splitter[3] to avoid the signal loss intrinsic to the passive (hybrid) splitters.

The initial frequency multiplication stages[4] are designed to multiply the 10 MHz signal to a frequency suitable for direct (×N) multiplication to the microwave range via a varactor-based comb generator. The frequency multiplication is split into three stages: a doubler, 10 to 20 MHz, followed by a tripler from 20 to 60 MHz and an additional tripler from 60 to 180 MHz. All triplers are based on push-pull transistor implementations to naturally increase the suppression of the second and fourth harmonic components from the multiplied spectrum, enhancing the efficiency at odd harmonics. The doubler is based on a classic full-wave rectifier, which provides by proper balancing a significant suppression of the fundamentals and odd harmonics instead.

The output from the 180 MHz multiplier is fed to a varactor-based comb multiplier, which exploits the nonlinear behavior of a varactor diode junction to step-up the signal to 3.60 GHz (x 20) and 7.02 GHz (×39). Actually, the comb generator produces a continuous comb of spectral components spaced 180 MHz apart; the required components at 3.60 and 7.02 GHz are filtered out by coaxial filters.

The 7.02 GHz signal is used in the maser receiver. The 3.6 GHz signal must be cleaned by the residual nearby components by use of a dielectrically stabilized (DRO) microwave oscillator. In order to keep the resulting components spaced enough far away to clearly lock the DRO on the right frequency, the selected components out of the comb generator are not the nearest ones to the nominal 3417.3415 MHz frequency, but are farther apart than about 180 MHz to allow for a safe discrimination when locking the DRO. The same holds true for the FM-modulated 2.685 MHz modulation frequency[5].

Considering the modulation as an additional component of the microwave modulation signal synthesis, we start from a square-wave FM modulated signal[6] at 2.6585 MHz. This will be translated (and not multiplied) to the microwave frequency, in order not to degrade the phase noise by the square of the order of the multiplication. Hence, this allows one to relax somewhat the phase noise specifications on the DDSs. Modulation depth shall be around ±170 Hz to cover the atomic transition line width. The modulation (interrogation) rate should be about 80 Hz for a square-wave modulation to comply with signal relaxation requirements (≈ 1 ms) due to the Q of the atomic resonator.

Following this approach, the modulating signal, an 80 Hz square wave, will be directly applied to the DDS to switch the frequency control registers between the two preset frequencies, each settable with high resolution. A free-running astable oscillator will asynchronously[7] generate the square wave

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[3] The active splitter provides a better port-to-port isolation, typically between 40 and 60 dB between output and input (at 10 MHz) and more than 60 dB between outputs.

[4] Various possibilities have been examined, and the one selected fulfills the requirements of providing also signals for other internal uses, such as for the 60 MHz DDS's reference.

[5] This can be turned also into a PM modulation, but for the moment being we will restrict our discussion to the square-wave FM modulation scheme.

[6] The frequency of this signal has been chosen as a reasonable compromise between two opposite constraints. One is the necessity of keeping a low phase noise and spuriousness from the signal generated by the DDS (frequency as low as possible with respect to the DDS clock). The other is the necessity to have a frequency as high as possible to facilitate frequency separation and filtering in the following stages of the up-conversion.

[7] With respect to the local reference (OCXO)

modulation signal. The resulting modulated signal at 2.6585 MHz is then mixed[8] with a 180 MHz signal from the primary multiplication chain to generate 182.6285 MHz. The other sideband is suppressed by the use of an image suppression mixer (single sideband mixer) or by appropriate filtering.

Consider the DRO operating at 3417.3415 MHz. Adding to this frequency the previous signal at 182.6285 MHz will produce a beat component at 3.6 GHz. This can be phase-compared with the 3.6 GHz component output by the comb generator, and the appropriate component of the resulting product signal is then used to phase-lock the DRO. The advantage of this approach results in an improved discrimination of the desired components from images due to the multiplication in the up-conversion chain. The filtered phase detector inputs need to discriminate only between signals that are 180 MHz (182 MHz) apart and, therefore, well within the lock bandwidth[9] of the DRO. The output of the DRO is then passively split to allow feedback to the second mixer in the synthesis chain and to allow driving the output power amplifier feeding the E/O modulator at 790 nm.

The second functional block is the Rb-maser receiver (Figure 5). As a result of the resonance interrogation, a microwave signal appears in the cavity when the average optical (and microwave) frequency modulating the laser is centered on the atomic resonance. The maser signal is detected by a coupling (pick-up) loop and fed to a low-noise amplifier (LNA). The expected level at the output of the cavity is about -90 dBm at 6834.683 MHz, and the first LNA boosts the signal of +25 dB. The signal chain budget is shown in Figure 5 and account is given for the nominal losses/gain of the various stages.

The receiver is a classical super-heterodyne architecture based on a double conversion. The first down-conversion translates the input signal to a first IF frequency of 185.317 MHz. The local oscillator (LO) is a DRO at 7020 MHz locked to one of the output lines of the comb generator. Alternatively, if the signal level suffices, the filtered output of the comb generator can be amplified to a suitable level to drive the mixer, and to act directly as a first LO for the first down-conversion mixer. This is feasible, since some additional filtering and unwanted components rejection is already provided by the tuned amplifiers of the first IF strip. This first IF provides an additional gain of +30 dB.

A 180 MHz signal[10] derived from the microwave modulation signal synthesis chain acts as a LO signal for the second down-conversion to a second IF at a frequency of 5.317 MHz. The second IF provides an additional gain of +40 dB. The signal is then AM-demodulated to produce the 80 Hz demodulation signal.

A low noise a.c. amplifier boosts the recovered 80 Hz square-wave signal that is fed to a synchronous detector to produce the error signal for the frequency-locked loop. The local reference for the synchronous detection is a replica of the 80 Hz modulating signal to the first DDS in the microwave modulation signal synthesis chain, suitably phase-shifted to compensate for the accumulated delay in the electronics and the resonance cell of the received signal.

Transitions in the interrogation frequency across the atomic resonance line width produce slow transitions in the recovered error signal, decaying with a time constant comparable to the line width of the atomic resonance acting as a frequency discriminator. These occur immediately after the signal

[8] This is a double-balanced mixer, suppressing the carrier; we have considered also the possible use of an image rejection mixer to facilitate suppression of the unwanted component resulting from the up-conversion process.
[9] The loop bandwidth for the DRO in these applications is intended to optimize the phase noise performance of the device by locking to a point in which the phase noise curve of the DRO intersects the reference (the 10 MHz multiplied to 3.4 GHz). This generally occurs at Fourier frequencies from the carrier in the order of 10 to 100 kHz depending upon the characteristics of the DRO, and therefore the loop time constant is generally chosen to be in the range between 10 and 100 μs.
[10] This is a +10 dBm minimum signal, so it is already suited to directly drive a mixer.

switchover driven by the 80 Hz modulation, and therefore appear as exponentially decaying rise and fall times following the transitions of the 80 Hz square wave. A monostable multivibrator is triggered by the same transitions (at 160 Hz) to produce a gating signal to a track-and-hold circuit, placed after the synchronous demodulator to remove these unwanted transitions.

The main loop integrator follows (this is an integrator with damping for stability reasons) to transform the error signal into a frequency control voltage locking the 10 MHz OCXO. In the present prototype, no automatic acquisition signal is foreseen; the operation of resetting the integrator and adjusting the unlocked free-running frequency of the OCXO being carried on manually with ease by the operator.

A few words on the lock detector: this is implemented as a combination of logical *and* between the detection of the presence of the second harmonic on the error signal prior to synchronous detection and the absence of the first harmonic (fundamental) on the same signal. Signal components detection is carried on by simple PLL tone detectors[11], and some logic gates will do the rest.

CHANGES FOR DEMODULATING A SQUARE-WAVE PHASE MODULATION INSTEAD OF A FREQUENCY MODULATION (ERROR SIGNAL)

The modifications to the circuit are straightforward. On the modulating side, the DDS needs to be switched between two phase values stored in two phase registers instead than between two frequency values.

However, a consideration is in order. Since frequency is the integral of the phase, for phase demodulation the error signal information is just contained in the first derivative of the signal, i.e., in the transitions of the square-wave signal. While for sine-wave modulation this is not an important issue, for square-wave modulation it is convenient to maximize the error signal signal-to-noise ratio by increasing the frequency to a higher value than the one normally used for frequency modulation (80 Hz)[12]. Therefore, the modulating period for phase modulation shall be comparable with the decay time of the first derivative of the error signal, decay time due to the finite Q of the atomic transition. A modulation rate around 300 ÷ 500 Hz is considered.

Modulation type	Modulation frequency, f_{mod}	DDS set	Track/Hold set
Square-wave, frequency	≈ 80 Hz	Load and switch frequency registers	T/H mode under control of $2 \cdot f_{mod}$
Square-wave, phase	≈ 400 Hz	Load and switch phase registers	Track only mode (disabled)

Table 1. Configuration for frequency and phase modulation of the interrogation signal.

On the receiving side, the track-and-hold circuit should be disabled, i.e.: continuously set in the track state, and no further modifications are envisaged. With these straightforward extensions, the circuit shall be able to operate with both sine- and square-wave frequency and phase modulation, to allow the experimental verification of the maser performances in all these cases.

[11] Fundamental and second harmonic detection can be implemented also with synchronous detectors, but it is an unnecessary complication and is not really required for the basic lock detection function.
[12] This lower frequency is due to the fact that we want to maximize instead the error signal usable time interval after the decay corresponding to the transition of the square-wave modulating signal.

LASER STABILIZATION LOOP

This is a classical frequency-locked loop (Figure 6), where a cell filled with Rb^{87} vapor acts as a frequency discriminator (absorption spectroscopy). A lock-in amplifier scheme is implemented to recover the error signal, with a sine-wave FM signal at 50 kHz modulating the laser current. A synchronous detector recovers the error signal, which is fed back to the laser diode to lock its center frequency to the atomic resonance.

In the case in which a separate Rb resonance cell is used for laser stabilization, a very small frequency offset must be added to the 790 nm radiation used for optical interrogation. The frequency offset arises from the fact that the laser diode stabilization cell will be filled with Rb^{87} only to allow for a narrower line width and improved frequency stabilization of the diode laser on the optical atomic resonance. The absence of the buffer gases in the laser stabilization cell shifts the optical resonance of a frequency offset estimated to be around 200 MHz. The synthesis circuit is straightforward and exploits an additional high-frequency DDS to generate the required frequency offset. Then the signal is bandpass-filtered and amplified to drive an acousto-optical (A/O) modulator that translates the laser frequency of the corresponding amount.

CONCLUSIONS

The IEN has proposed and is developing on a novel atomic oscillator with performances expected to lay in between[13] the traditional Rb optically pumped frequency standard and a passive H-maser, with a size comparable to the former. In respect to the specification required by ESA, the design of the CPT Rb maser will mainly focus to the demonstration of the stability goals. Mass, volume, power consumption, sensitivity to vibration and acceleration, and lifetime requirements cannot be met at this stage of the development, because this requires optics and electronic integration. Integration is an expensive undertaking that can be justified only after the frequency stability behavior of the device has been assessed. The design, implementation, and testing will be completed by mid-2003 and then performance results will be available to justify the follow-on engineering of the Rb CPT maser for possible space applications.

REFERENCES

[1] A. Godone, F. Levi, and S. Micalizio, 2002, *"Coherent Population Trapping Maser,"* Editrice C.L.U.T.

[2] J. Kitching, S. Knappe, N. Vukicevic, L. Hollberg, R. Wynands, and W. Weidmann, 2000, **IEEE Transactions on Instrumentation and Measurement, IM-49**, 1313.

[3] J. Vanier, A. Godone, and F. Levi, 1998, **Physical Reviews A58**, 2345.

[13] Both standards form the current baseline for spaceborne clocks for the ESA GALILEO system.

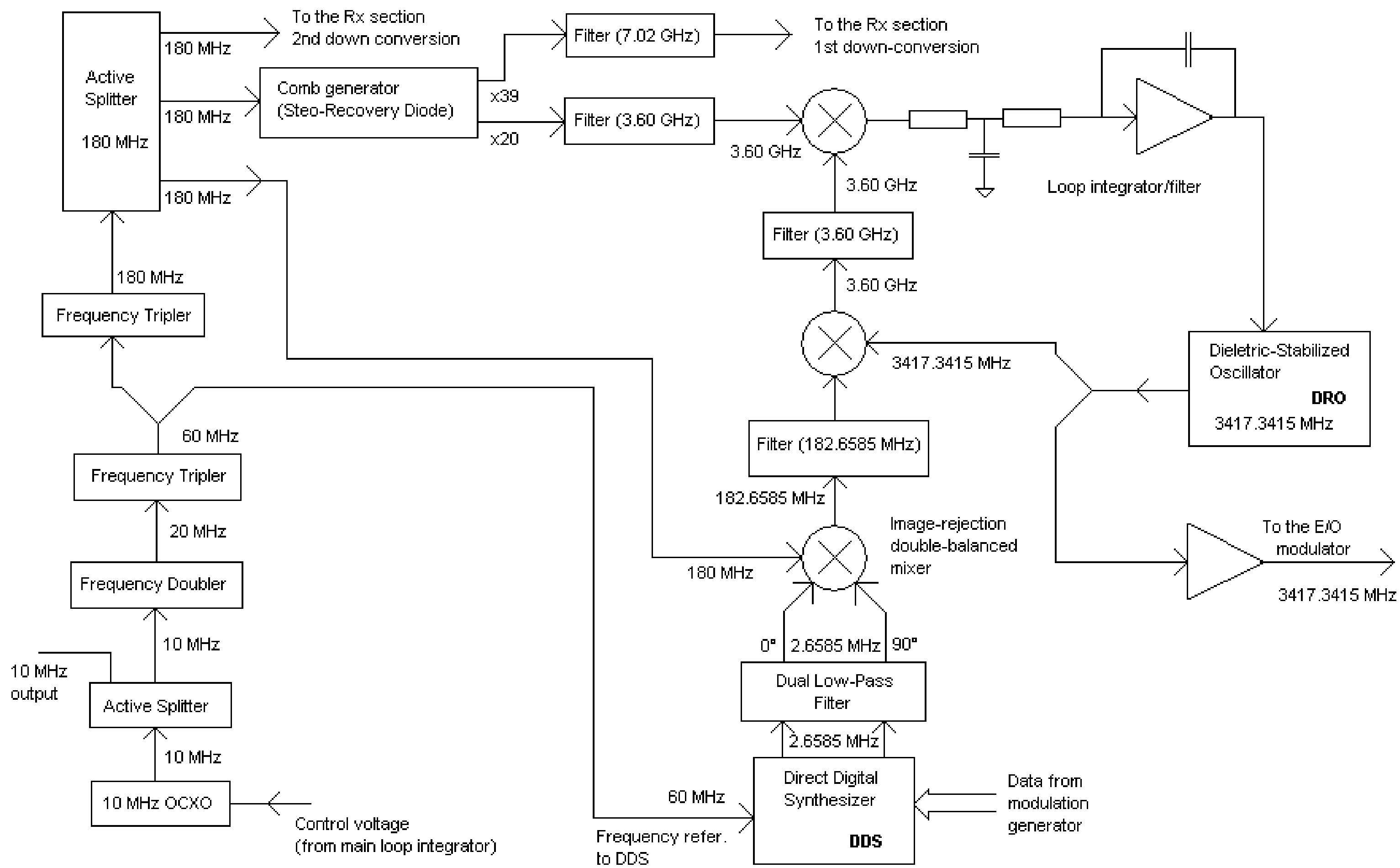

Figure 4. Microwave synthesis architecture.

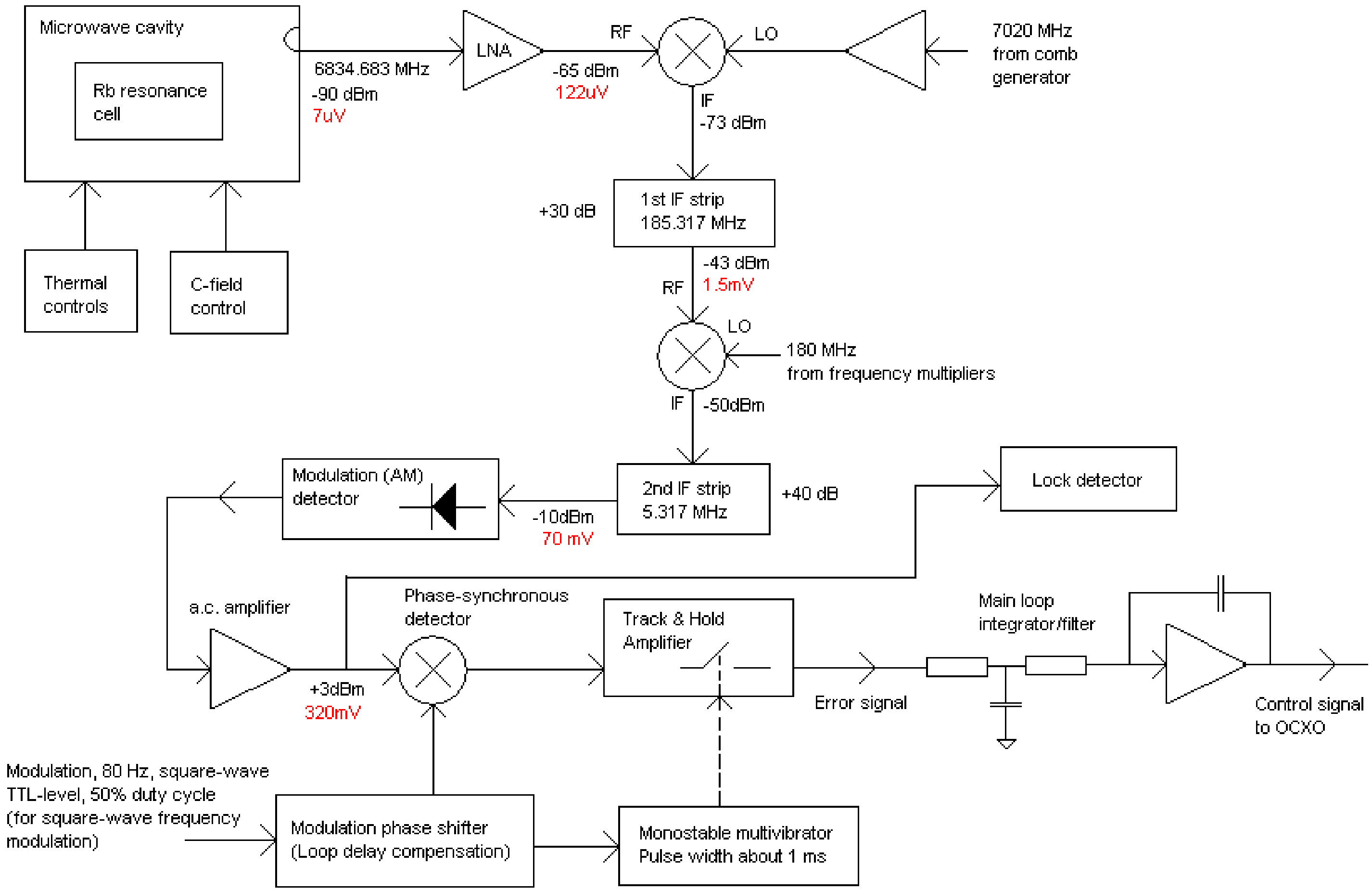

Figure 5. Maser receiver architecture.

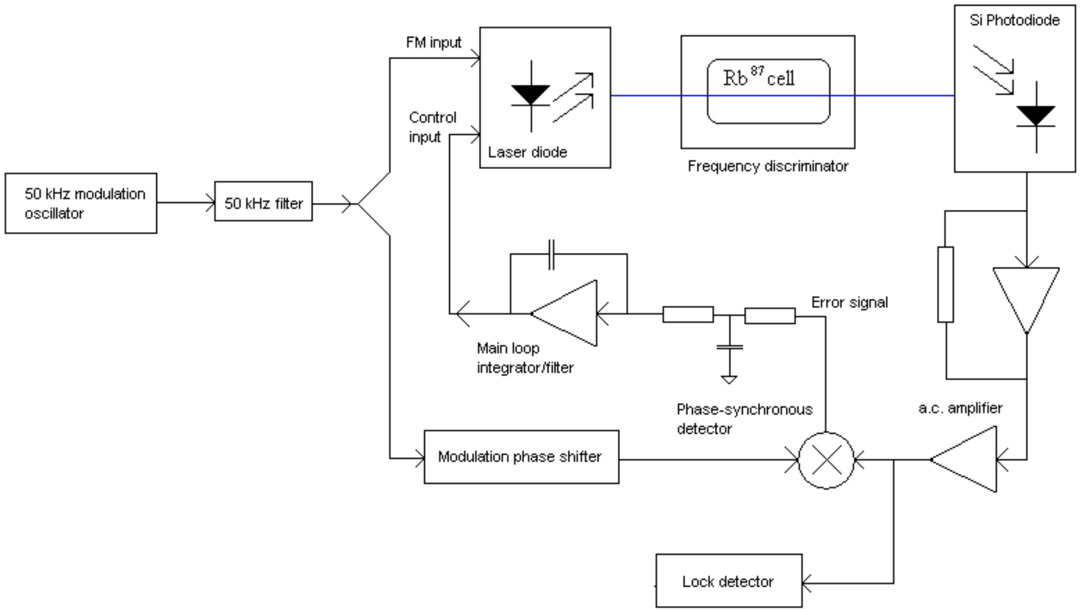

Figure 6. Laser stabilization loop.