On the Flicker Noise of Ferrite Circulators for Ultra-Stable Oscillators

Enrico Rubiola, Yannick Gruson, and Vincent Giordano

***Abstract*—The flicker noise of the ferrite circulator is a critical element in ultra-stable microwave oscillators, in which the signal reflected from the input of the reference cavity is exploited to stabilize the frequency. This paper explains why the circulator noise must be measured in isolation mode, proposes a measurement scheme, and provides experimental results. The observed flicker spans from −162 to −170 dB[rad^2]/Hz at 1 Hz off the 9.2 GHz carrier, and at +19 dBm of input power. In the same conditions, the instrument limit is below −180 dB[rad^2]/Hz. Experiments also give information on the mechanical stability of the microwave assembly, which is in the range of 10^{-11} m. The measurement method can be used as the phase detector of a corrected oscillator; and, in the field of solid-state physics, it can be used for the measurement of random fluctuations in magnetic materials.**

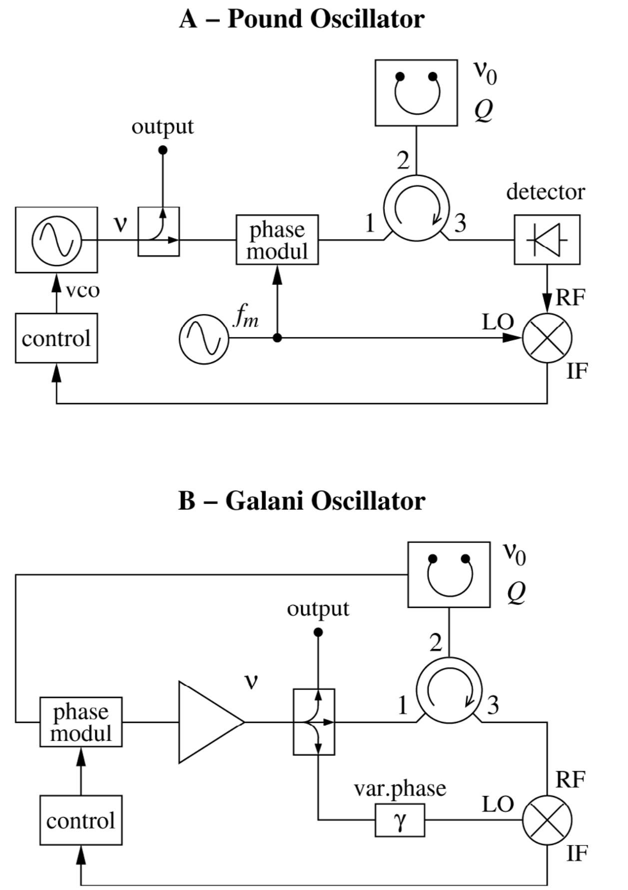

Fig. 1. Ultra-stable microwave oscillators.

I. Introduction

The analysis of ultra-stable microwave oscillators reveals that the present configurations rely upon two basic schemes proposed by Pound [1] and by Galani *et al.* [2]. In the Pound scheme [Fig. 1(a)], an oscillator is frequency locked to a reference resonator by measuring the frequency error, which is obtained from the signal reflected by the resonator. In the Galani scheme [Fig. 1(b)], a reference resonator is used in transmission mode to loop the signal back to the amplifier input. In addition, the signal reflected by the resonator provides the error signal used to correct for the amplifier noise. A mixed configuration is sometimes used [3], which consists of a Galani oscillator in which the detection system is replaced with that of the Pound scheme.

The main idea of the stabilized oscillator is that an error signal, obtained from the microwave signal reflected by the reference resonator, is used to correct the oscillator frequency through an appropriate noise-degeneration circuit that exploits the stability of the resonator. To do so, reflection is always preferred to transmission, and a ferrite circulator is used to extract the reflected signal. The reasons for this choice are the low loss and the low white noise of the circulator, and simplicity. Yet, the flicker noise of the circulator is a good candidate to limit the oscillator stability through the phase-to-frequency conversion mechanism known as the Leeson model [4]. This mechanism is effective at Fourier frequencies below the cutoff frequency $f_L = \frac{\nu_0}{2Q}$ of the resonator. For reference, a $\nu_0 = 10$ GHz whispering gallery resonator that exhibit a merit factor $Q = 2 \times 10^5$ at room temperature has a cutoff frequency $f_L = 25$ kHz.

The circulator consists of a ferrite cylinder with three ports at 120°, biased by an axial direct current (DC) field that induces Larmor precession. The biased ferrite is gyrotropic, which means that the magnetic permeability μ seen by the waves propagating circularly in the cylinder splits into μ^- and μ^+, depending on the direction with respect to the precession. The velocity of electromagnetic waves, proportional to $1/\sqrt{\mu}$, is split accordingly. Circulation results from the interference between the precessionwise and counter-precessionwise modes, which is additive at the transmission port and destructive at the isolation

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E. Rubiola is with the Université Henri Poincaré Ecole Supérieure de Sciences et Technologies de l'Ingénieur de Nancy (ESSTIN) and the Laboratory of Physics of Ionized Media and Applications (LPMIA), Nancy, France (e-mail: rubiola@esstin.uhp-nancy.fr).

Y. Gruson and V. Giordano are with the Franche-Compté Electronique, Méchanique, Thermique, Optique-Science Technologie (FEMTO-ST) Institute, Dept. Laboratoire de Physique et Métrologie des Oscillateurs (LPMO), Besançon, France.

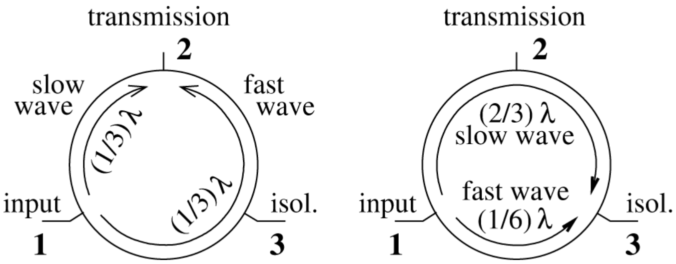

Fig. 2. Circulation effect.

port, as shown in Fig. 2. Yet, reality is more complex than in Fig. 2 because circulation results from the field in the whole volume of the ferrite. If port 3 is internally terminated, the device is an isolator. Most of the fundamental work on the circulators dates to the sixties [5]–[9], while high-order mode circulators are more recent [10], [11].

A bibliographical research shows that little attention has been given to noise, and that only the theory of thermal noise has been developed, based on thermal equilibrium and on the properties of the scattering matrix [12], [13]. No theory of the flicker noise has been found. But [14] contains a section on the circulator noise that provides $1/f$ coefficients and suggests that flickering can be connected to the reflection coefficient Γ. Two articles [15], [16] report experimental data on a circulator used as an isolator. Yet, the suitability of these results to the noise-corrected oscillator is arguable, for the reasons detailed below. Looking at Fig. 1, the circulator noise directed outward from port 3 goes to the input of the phase detector, hence it contributes to the frequency instability. Conversely, the circulator noise affecting the path from port 1 to port 2 (transmission) is not turned into frequency noise because it is compensated by the noise degeneration loop. There remains some phase noise, depending on the location of the output tap; but, in the absence of the $\varphi \to f$ conversion, this is a minor problem. Having in mind the application in ultra-stable oscillators, the circulator noise must be measured at the isolation port instead of at the transmission port.

II. Measurement Method

The circulator is inserted in a test circuit, shown in the dashed frame of Fig. 3. The test circuit simulates the insertion of the circulator in an oscillator. The 16 dB attenuator shorted at one end replaces a cavity whose reflection coefficient is $|S_{11}| = -32$ dB, which is typical of our 10 GHz room-temperature whispering gallery resonators [17]. The simulated cavity is virtually free from relaxation time and from flickering. We are interested in the flicker region, which turns out to be below a few kilohertz. This maximum frequency is a factor 10 lower than the cutoff frequency f_L of the whispering gallery resonator, and much lower than that of any other type of microwave resonator at room temperature. The input impedance of the true resonator, therefore, is constant in the frequency range of interest, which is necessary in order to replace the resonator with the shorted attenuator without perturbing the circulator port.

The complete measurement system of Fig. 3 is a multistage carrier suppression interferometer, with amplification and vector detection of the noise sidebands. The theory of operation is the same as the 100 MHz instrument fully described in [18]. Nonetheless, microwave frequencies require a different technology and a more stable mechanical implementation.

The circulator attenuates the carrier by some 25–30 dB. This is $|S_{31}|$ of the whole test circuit, including the imperfect isolation of the circulator. Then, the carrier is attenuated as much as possible by vector addition of an opposite signal through the 10 dB coupler. A high carrier rejection is needed to prevent the amplifier from flickering by nonlinear up-conversion of the DC bias noise. The circulator noise sidebands:

$$x(t) = n_1(t)\cos(2\pi\nu_0 t) - n_2(t)\sin(2\pi\nu_0 t), \qquad (1)$$

not affected by the interference mechanism, are amplified and down converted to baseband by the I-Q detector. Taking $\cos(2\pi\nu_0 t)$ as the phase reference, $n_1(t)$ and $n_2(t)$ are related to the amplitude and phase noise at the transmission port of the circulator by:

$$\alpha(t) = \frac{n_1(t)}{V_0} \text{ and } \varphi(t) = \frac{n_2(t)}{V_0}, \qquad (2)$$

where $V_0 = \sqrt{2R_0P_0}$ is the peak voltage; the device loss, of some 0.2 dB, is neglected. By inspection on Fig. 3, and temporarily setting $B = G = I$ (identity matrix), the detected signal is:

$$\begin{bmatrix} w_1(t) \\ w_2(t) \end{bmatrix} = \sqrt{\frac{g'g''}{\ell_c \ell_m}} \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix}, \qquad (3)$$

where ℓ_c is the insertion loss of the 10 dB coupler, ℓ_m is the single-sideband (SSB) loss of the I-Q detector, and ψ is the arbitrary phase that results from the circuit layout. Combining (2) and (3) we get:

$$\begin{bmatrix} w_1(t) \\ w_2(t) \end{bmatrix} = k_{\text{dsb}}\sqrt{P_0} \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \alpha(t) \\ \varphi(t) \end{bmatrix}, \qquad (4)$$

where $k_{\text{dsb}} = \sqrt{2g'g''R_0/\ell_c\ell_m}$ is the dual sideband (DSB) gain of the instrument. For (3) and (4) to be true, it is necessary that the two channels of the I-Q detector are equal and orthogonal. This is fixed by the matrix G, whose coefficients are determined with the Gram-Schmidt process [19]. And (3) and (4) also contain the arbitrary phase ψ that results from the circuit layout. The matrix B provides the frame rotation by which the output signal $[w_1, w_2]^T$ (the superscript T stands for transposed) can be made proportional to $[\alpha, \varphi]^T$, or to the scalar projections of $[\alpha, \varphi]^T$ on any desired pair of Cartesian axes. The advantage of introducing B is that the frame rotation is done after detecting instead of in the microwave section. The product BG can

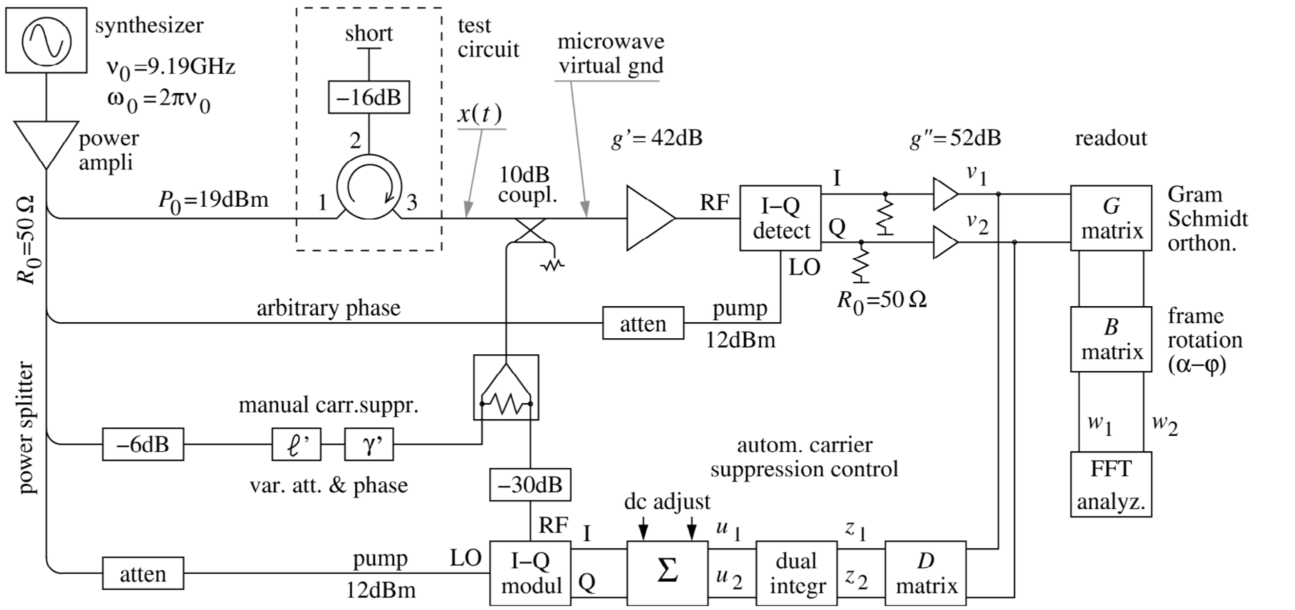

Fig. 3. Scheme of the instrument.

be moved to the fast Fourier transfer (FFT) analyzer or to an external computer, which saves some hardware.

The carrier is automatically suppressed in closed loop. The diagonalization matrix D transforms the control into two independent loops that work in Cartesian coordinates. A previous paper [18] provides the theory and the details needed to put the control to work. Interestingly, the control is independent of the test circuit and of P_0.

The following information may be useful to duplicate our experiment. The residual carrier does not exceed -80 dBm at the amplifier input, which is some 100 dB below the circulator input power. The amplifier is split into two stages with a 100 MHz bandwidth filter in between, which ensures linear—hence flicker-free—operation. The path ℓ'–γ' provides the fine carrier suppression needed to pull the control in. This is necessary because low flicker design imposes a low weight (-43 dB) of the signal from the I-Q modulator. The loop bandwidth is set to 0.3 Hz, so that the control has no effect on the measured spectra above a few hertz. The DSB gain is $k_{\text{dsb}} = 75\ \text{dBV}/\sqrt{\text{mW}}$. This is measured by observing the output spectrum when the output of the test circuit (port 3) is replaced with a white noise source of known spectrum. Alternatively, a sinusoidal source of frequency ν_s a few kilohertz off ν_0 can be used, from which $k_{\text{ssb}} = k_{\text{dsb}}/\sqrt{2}$ is measured. The measurement uncertainty is of some 1 dB, mainly due to the imperfect measurement of the reference signal.

III. Experimental Results

The background noise of the instrument is measured by replacing the test circuit with a 30 dB attenuator connected between ports 1 and 3. This simulates a nearly noiseless circulator that shows the same isolation of the real ones, and the rest of the instrument works in substantially unchanged conditions. The white noise is of

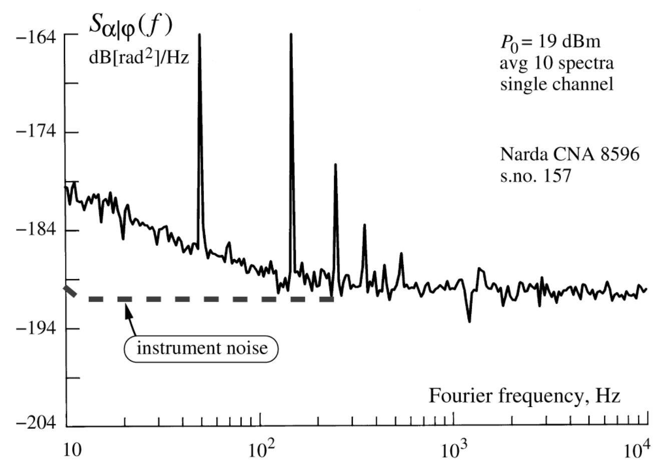

Fig. 4. Example of measured spectrum.

-191 dB[rad^2]/Hz. This value is consistent with the expected value that results from $P_0 = 19$ dBm and from the noise figure $F = 2$ dB of the amplifier. As the detection frame is set by the matrix B, we use the notation dB[rad^2]/Hz to indicate that the unit of angle [rad] appears only in the measurement of φ. The residual flicker of the instrument is of some -180 dB[rad^2]/Hz at $f = 1$ Hz off the carrier.

All the spectra are measured in the 10–10^4 Hz span. Fig. 4 shows an example. The noise sidebands are normalized to the input power P_0. Neglecting the low loss of the circulator, this choice is consistent with the phase-noise mechanism of the oscillator. The $1/f$ coefficient of the circulator noise is extrapolated from the 10–100 Hz decade, which is based on the polynomial approximation [20]. Being interested in $1/f$ noise, we could not measure the 1–10 Hz decade because a higher slope, f^{-2}, appears at $f \approx 1$ Hz. This is thought to be due to the fluctuations of the room temperature, which affect either the instrument or the circulator. Instead of calibrating the detection direction, we decided to search for the minimum and maximum flicker noise, i.e., the semiaxes of the noise ellipse, by sweeping the detection angle through the matrix B.

Six circulators have been measured, suitable to the 8–12 GHz range, and selected with the sole criterion that they are routinely used in our laboratory for ultra-stable oscillators. Equal or similar circulators are used for the same purpose at the Jet Propulsion Laboratory, Pasadena, CA, at the National Physical Laboratory, London, UK, and at the University of Western Australia, Perth. For reference, we also measured an old waveguide isolator used in reverse mode. Table I shows the results.

The column labeled "Oscillator" in Table I reports the two-sample (Allan) deviation $\sigma_y(\tau)$ of the fractional frequency fluctuation $y = \frac{1}{2\pi\nu_0}\frac{d\varphi(t)}{dt}$ of an otherwise perfect oscillator that makes use of the circulator. The conservative assumption is made that the worst noise value is taken as it was true-phase noise, regardless of ψ. The merit factor is $Q = 2 \times 10^5$, typical of a room-temperature 10 GHz whispering gallery resonator. With $1/f$ frequency noise, σ_y is independent of τ. The σ_y is calculated from:

$$\sigma_y^2 = 2\ln(2)\frac{1}{4Q^2}S_\varphi^{\text{flicker}}(1\text{ Hz}), \tag{5}$$

which combines the Leeson model [4] and the spectrum-to-variance transformation [20]. As a further consequence, the system of Fig. 3 can be used as the detector of the noise degeneration circuit in an oscillator. Assuming a stable cavity with $Q = 2 \times 10^5$, the circulator would limit the frequency stability to parts in 10^{-14}.

IV. Mechanical Stability

The measurement of $1/f$ noise in circulators gives some information on the mechanical properties of microwave circuits. This unexpected benefit deserves a separate section.

A phase fluctuation $\varphi(t)$ can be regarded as an equivalent fluctuation of length $l(t) = \frac{\lambda}{2\pi}\varphi(t)$. Thus:

$$l(t) = \frac{1}{2\pi}\frac{c'}{\nu_0}\varphi(t), \tag{6}$$

where $c' \approx 0.8\,c$ is the group velocity in the circuit. Having measured $S_\varphi(f)$, we know the spectrum of length fluctuation:

$$S_l(f) = \left(\frac{1}{2\pi}\frac{c'}{\nu_0}\right)^2 S_\varphi(f). \tag{7}$$

Representing the noise spectrum as the power-law:

$$S(f) = \sum_\alpha h_\alpha f^\alpha, \tag{8}$$

the flicker term $h_1 f^{-1}$ can be transformed into the Allan deviation $\sigma(\tau)$ through:

$$\sigma^2 = 2\ln(2)\,h_{-1}. \tag{9}$$

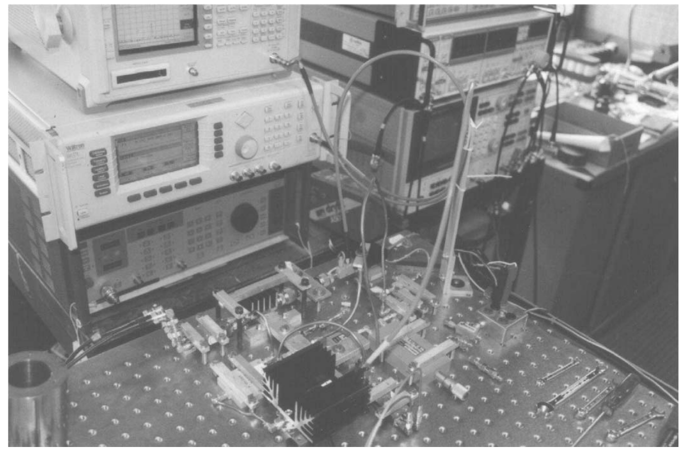

Fig. 5. Microwave section of the experimental setup.

In the domain of time and frequency, (8) is usually written as $S_y(f) = \sum_\alpha h_\alpha f^\alpha$, and (9) as $\sigma_y^2(\tau) = 2\ln(2)\,h_{-1}$, where y is the fractional frequency fluctuation. Nevertheless, (9) is a mathematical property of spectra, which is independent of the physical quantity involved. Thus (9) can be used with the length fluctuation (6), from which we can calculate the Allan deviation:

$$\sigma_l = \sqrt{2\ln(2)\,h_{-1}}, \tag{10}$$

of the equivalent length fluctuation l. Once again, here h_{-1} is the $1/f$ coefficient of $S_l(f)$, not of $S_y(f)$.

The (10) explains the equivalent mechanical stability reported in the right column of Table I. With a circulator, σ_l has a simple physical meaning because noise results from the interference of two separate signal paths. Conversely, the instrument stability (4.9 pm) is a more abstract entity that derives from the electrical noise that remains when the circulator is replaced with an attenuator. The measured data are of parts in 10^{-11} m. One can figure out how small this value is by comparing it to the Bohr radius, which is $a_0 = 5.29 \times 10^{-11}$ m. This explains the unusual microwave assembly shown in Fig. 5, mounted onto a standard 0.6×0.9 m^2 breadboard of the type commonly used for optics. However careful our implementation is, it is based on standard microwave parts, which includes SMA connectors, PTFE-insulated semirigid cables, etc. The combined effect of magnetic fluctuations in the circulator, electric fluctuations (for example in the dielectric of cables), and mechanical fluctuations is in the 10^{-11} m range. Such high mechanical stability would not be a surprise in other domains, such as nonoptical microscopy, in which the attainable resolution is well below 1 pm [21]. However, the existence of a flicker floor of mechanical stability in nonoptical microscopy seems not to have been identified clearly yet, hidden by other problems.

V. Discussion

The flicker noise of the circulator is due to the near-DC fluctuations that modulate the microwave carrier. There

TABLE I
Measured Noise for some Circulators.

Factory and device type	Ser. no.	$S_{\alpha\|\varphi}(1\ \text{Hz})$ dB[rad^2]/Hz min.	max.	Equivalent stability: Oscillator $\sigma_y(\tau)$, $\times 10^{-15}$	Mechanical $\sigma_l(\tau)$, $\times 10^{-12}$ m
Aercomm J180-124	1320	−165.1	−162.6	22	36
Dorado 4CCC 10-1[1]	101	−171.6	−168.0	12	19
Trak C80124/A	E001	−165.9	−160.3	28	47
	E003	−165.7	−164.0	19	31
Narda CNA 8596	157	−170.3	−170.3	9	15
	158	−170.3	−169.1	10	17
Sivers Lab 7041X[2]	625	−176.0	−164.0	n.a.	n.a.
Residual instrum. noise		<180			(4.9)

[1]Designed for cryogenic applications.
[2]Waveguide isolator.

results amplitude noise $\alpha(t)$ and phase noise $\varphi(t)$ that exhibit power spectral densities proportional to $1/f$. The microwave spectrum, therefore, is proportional to $1/|\nu-\nu_0|$ around the carrier frequency ν_0. As a circulator shows a typical bandwidth of less than one octave, the dependence on carrier frequency is a minor concern. Three possible noise mechanisms have been identified, namely:

- Barkhausen effect. The ferrite consists of a set of small volumes, called Weiss domains, in which the magnetic momenta are parallel. As a consequence of thermal energy, boundary atoms flip between contiguous domains, which results in $1/f$ noise [22].
- Magnetization noise. A fluctuation in the DC magnetic field affects the velocity of the slow wave and of the fast wave, for the position of the "dark fringe" fluctuates with respect to the isolation port. Magnetization noise differs from Barkhausen noise in that a fluctuation of the DC field acts on the ferrite bulk, for the random fluctuations of the two interfering waves are fully correlated. But with Barkhausen noise they are independent.
- Mechanical instability. A dimensional fluctuation results in random modulation of the microwave carrier, hence in noise. In addition to the electrical length fluctuation, mechanical instability can affect the DC bias through the reluctance of the magnetic circuit.

A major difficulty in ascribing the observed results to the above phenomena, or to other ones, derives from the lack of information about the internal structure of circulators. Nevertheless, we can provide some physical insight from observations as [15], [16] report $S_\alpha(1\ \text{Hz}) = -149$ dB/Hz and $S_\varphi(1\ \text{Hz}) = -154$ dB[rad^2]/Hz, which is 10–20 dB higher than our values. The circulator, similar to ours, was measured at the same frequency and driving power as we did, but in forward mode. Similar values are suggested in [14], still in forward mode, yet without reporting on actual measurements. Noise is 10–20 dB lower at the isolation port than at the transmission port, which makes one think that isolation and noise reduction go with one another. This seems incompatible with the Barkhausen noise because the two counter-propagating waves cross statistically independent regions, for the internal noise would add up at ports 2 and 3 in the same way. Conversely, a fluctuation of the DC bias or of the geometry acts deterministically on the two counter-propagating waves, which is in agreement with the observed behavior. If better isolation also reduces noise, the tuning technique proposed in [23] could be useful. The conjecture that isolation also reduces noise could be checked by measuring our circulators in forward mode. Unfortunately, at the present time, this cannot be done because the carrier suppression requires an additional attenuator and a phase shifter that work at $P_0 = 19$ dBm. Due to the power, the noise of these devices limits the low-frequency sensitivity. It should be remarked that the results reported in [15], [16] could have been obtained only by cascading a few devices.

State-of-the-art, room-temperature whispering gallery oscillators exhibit a stability of parts in 10^{-13}. As a matter of fact, this limitation is due to the thermal coefficient of the resonator. Looking at Table I, the circulator effect is one order of magnitude lower than the oscillator instability.

Temperature compensation is being studied mainly on cryogenic resonators. Three approaches are followed, namely, thermomechanical compensation of the resonator [24]; dielectric or paramagnetic compensation of the resonant frequency at a turning point induced by the presence of an external ruby element, of a rutile layer, or of Ti^{3+} impurities [24]–[27]; the difference in temperature coefficient between TE and TM modes, due to the anisotropy of the sapphire dielectric constant [28]. If these techniques ported to room-temperature resonators improve the stability by a factor of 10, the circulator noise is no longer negligible.

As an improvement, the circulator can be replaced with a directional coupler or with a Wilkinson coupler, which are virtually free from flickering. However, the white noise floor increases by the loss (intrinsic and dissipative) of the coupler. If the resonator power is limited by thermal gradients or by other internal phenomena while the amplifier does not suffer from such limitation, the scheme of Fig. 6 can be useful. The idea is that a 10–20 dB coupler shows a low loss in the critical path, from the resonator to the

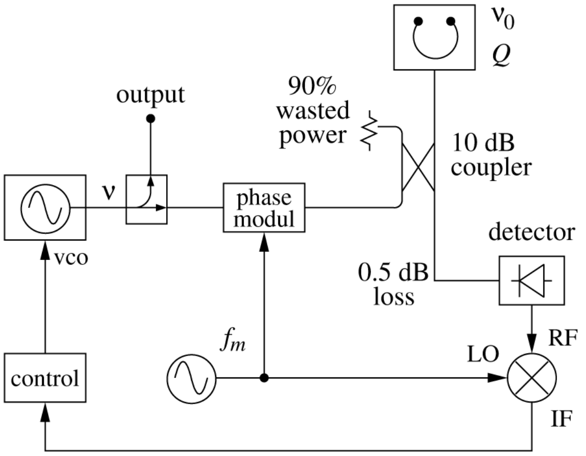

Fig. 6. The circulator of a Pound oscillator can be replaced with a directional coupler, at expense of some power loss. The extension to the Galani oscillator is obvious.

detector, and a part of the amplifier power can be wasted at a minimum cost.

Cryogenic oscillators at liquid He temperature exhibit a stability of a few parts in 10^{-15}. In the absence of a model to extrapolate the circulator noise, we guess that the noise is not worse than that measured at room temperature. If so, taking $Q = 5 \times 10^8$ at $\nu_0 = 10$ GHz as a conservative value and -160 dB as the circulator flickering, the limit predicted by (5) is $\sigma_y = 1.2 \times 10^{-17}$, which is far below the stability of present oscillators.

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Enrico Rubiola was born in Torino, Italy, in 1957. He graduated in electronic engineering in 1983 at the Politecnico, the technical university of Torino, and received the Ph.D. degree in metrology in 1988 from the Italian Ministry of Scientific Research in Rome.

After having been a researcher at Politecnico and a professor at the University of Parma in Italy, he is a professor within the Université Henri Poincaré (UHP) in Nancy, France. Dr. Rubiola is a researcher at the LPMIA, the Laboratory of Physics of Ionized

Media and Applications at the UHP. He teaches electronics at the ESSTIN (Ecole Supérieure de Sciences et Technologies de l'Ingénieur de Nancy), the state engineering school within the UHP, where he also is in charge of the Department of Electronics.

Dr. Rubiola has worked on various topics of electronics and metrology, namely, navigation systems, time and frequency comparisons, atomic frequency standards, and gravity. His main fields of interest are precision electronics and phase noise metrology, which include frequency synthesis, high spectral purity oscillators, and noise.

Yannick Gruson was born in Hazebrouck, France, on February 24, 1967. He received a master degree in microwaves engineering in 1994 from the University of Lille, Lille, France.

In 1995, he joined the Laboratoire de Physique et de Métrologie des Oscillateurs of Centre National de la Recherche Scientifique (CNRS), Besançon, France. He is an engineer of the permanent staff. His main area of interest is the development of low phase noise oscillators.

Vincent Giordano was born in Besançon, France, on February 20, 1962. He received the engineer degree (5 years degree) in mechanics in 1984 from the Ecole Supérieure de Mécanique et des Microtechniques, Besançon, France, and the Ph.D. degree in physical sciences in 1987 from the Paris XI University, Orsay, France. During 1984–1993 he was a researcher of the permanent staff of the Laboratoire de l'Horloge Atomique, Orsay, France, where he worked on a laser diode optically pumped cesium beam frequency standard. In 1993, he joined the Laboratoire de Physique et de Métrologie des Oscillateurs (LPMO), Besançon, France, where he is the head of the microwave metrology team.

His main area of interest is the study of high-spectral purity microwave oscillators and the high-sensibility phase noise measurement systems.