ear modeling, noise modeling, and temperature stabilization of hybrid and monolithic UHF oscillators utilizing composite resonators. Wang *et al.* [7] have recently described a similar resonator structure with temperature stabilities exceeding AT-cut quartz. Since composite bulk wave resonators have been demonstrated at frequencies above 1 GHz [8], work is now proceeding on fundamental-mode hybrid circuits at these frequencies. It is expected that integrated-circuit fabrication techniques will permit direct integration of the resonator with active devices on the same substrate resulting in a new class of RF/LSI-type circuits. Work is proceeding in this area.

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YIG Oscillators: Is a Planar Geometry Better?

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***Abstract*—Two yttrium-iron-garnet (YIG) oscillator technologies are compared: the more mature YIG sphere oscillator technology which is based on the uniform (resonant) precession of the electron spins in a small sphere of YIG, and the new planar YIG technology which utilizes the propagation of magnetostatic waves in an epitaxial film of YIG. The YIG sphere technology has been used for microwave oscillators for more than 25 years, but has two significant areas of difficulty in applications: the alignment of the YIG sphere in the magnetic bias field coupling cavity requires great precision and the gain element requires a negative resistance element to sustain oscillation. The MSW technology is much newer and less well understood, but the resonator elements are fabricated using a 50-μm line width planar technology making it an appealing candidate. Both technologies are reviewed herein with regard to resonant element theory, temperature, and noise characteristics. New data and theory are presented on MSW resonator optimization.**

I. BACKGROUND

OSCILLATORS using YIG spheres (YTO) have been made for more than 25 years. Recently, Zensius [1] reported a design for a YTO operating up to 40 GHz. The YTO sphere technology is quite mature. The YIG spheres are small (~ 0.5 mm diam), so the associated magnet designs are not overly complex. Considerable work has been reported on the choice of an orientation axis of the magnetic field for optimum temperature compensation. There are two design considerations that are not easy to overcome, however. The common choice for the resonator configuration is a one-port design, so the gain element must be operated in a negative resistance mode, as shown in Fig. 1. Also, the magnetic-field orientation and coupling loop alignments are rather complex, three-dimensional alignment procedures. The small size of the sphere and coupling loop means that the precision is comparable to watchmaking.

The advent of magnetostatic wave devices [2], [3] has included resonator elements fabricated in this planar technology. One apparent advantage of the planar versus the sphere resonators is that the loaded Q's are a factor of 5 larger for the planar resonators than for the sphere (~ 1000 versus 200). The magnetic field required at a given frequency for resonance is somewhat lower for the planar resonators. The planar resonators are more easily fabricated than the sphere resonators, the processing being exactly analogous to the MIC fabrication procedures. MSW

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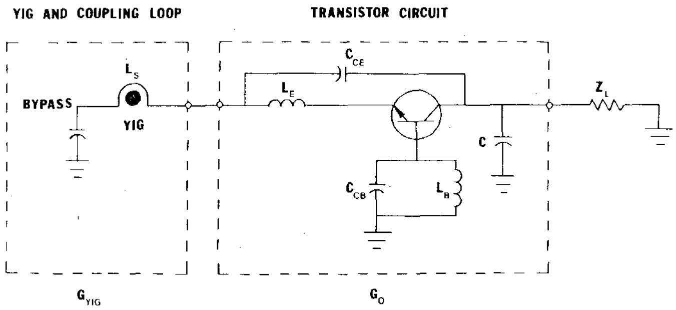

Fig. 1. Typical YIG sphere oscillator.

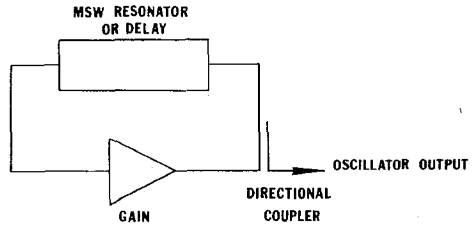

Fig. 2. MSW feedback oscillator.

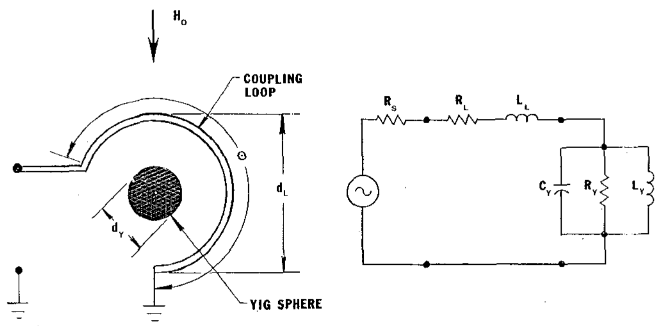

Fig. 3. YIG sphere resonator equivalent circuit.

oscillators of the delay-line- or resonator-type utilize a feedback circuit, as shown in Fig. 2. Magnet design is much more difficult, however, since the planar YIG resonators are as large as 3×25 mm. There has been no work yet on an optimum propagation orientation for temperature characteristics in a planar YIG resonator, although some temperature stabilization schemes have been explored.

II. Resonant Element Theory

The YIG sphere resonator operates as a result of the excitation of uniform precession modes of spin waves in the YIG material. The resonant precession frequency f_0 is given [4] by

$$f_0 = \gamma H_0$$

where γ is 2.8 MHz/Oe and H_0 is the applied field. Osbrink [5] has reviewed the fundamentals of the YTO oscillators recently. The frequency range over which the sphere can be successfully used is determined by the saturation magnetization $4\pi M_s$ of the YIG. (For pure YIG, $4\pi M_s = 1760$ Oe.)

$$\gamma(4\pi M_s)/3 < f < 2\gamma(4\pi M_s)/3.$$

The lower limit corresponds to the minimum external field (with the demagnetization factor of a sphere) required for saturation. The upper limit corresponds to the onset of nonlinear effects [6].

The equivalent circuit of a YIG sphere resonator [7] is shown in Fig. 3. The circuit elements are given by

$$L_y = \mu_0 V K^2 \omega_m / \omega_0$$
$$R_y = Q \omega_m \mu_0 V K^2$$
$$V = 4\pi d_y^3 / 3$$
$$\omega_m = 2\pi\gamma(4\pi M_s)$$
$$K = \Theta/(360 d_l)$$
$$Q_y = R_y/\omega_0 L_y = H_0/\Delta H$$
$$Q_{ex} = R_{ex} Q_y / R_y$$

where μ_0 is the free-space permeability, d_y is the sphere diameter, d_l is the coupling loop diameter, Q_y is assumed to be the material Q, ΔH is the FMR line width, and Θ is the coupling angle. If an external circuit with R_{ex} impedance is attached to the YIG sphere resonator, the external Q is given by Q_{ex}, for $R_{ex} < R_y$.

Consequently, although the Q_y is a measure of the intrinsic merit of the resonator, the merit of the resonator when used in an oscillator circuit is determined by the Q_y/R_y ratio. Since the Q_{ex}/Q_y ratio is often less than 10^{-1} and R_{ex} is 10–100 Ω, we expect R_y to be $\sim 10^3$ Ω. The material limited $R_y \sim 2\times 10^4$ Ω for $\Delta H = 0.3$ Oe, $4\pi M_s = 1760$ Oe and light coupling. This treatment ignores the effects of sphere surface quality, field inhomogeneity, and loop conductivity.

The planar YIG structures will be subject to similar constraints— that is, the Q will be limited by the material line width. The pertinent parameter required then is the dissipative quantity for the planar structures which is analogous to the R_y in the YIG sphere. Castera *et al.* [6] have derived an equivalent circuit for an MSFVW (forward volume wave) resonator from S-parameter measurements and report the values of dissipative elements to be 200 Ω. This is consistent with the observation that the external Q of the planar YIG resonators (both MSSW, surface wave and MSFVW devices) have loaded Q's of greater than 500, whereas the YIG sphere resonators loaded Q's are less than 300. Since the dissipative elements of the planar YIG structure appear to be of a value that offers a better match than the YIG spheres to available active elements (and hence higher loaded Q), it is expected that the planar structures hold greater potential for use in oscillators.

III. Resonator Temperature Characteristics

The magnetic properties of YIG are temperature dependent, so elaborate procedures are used to minimize temperature effects on the YIG sphere and magnet structure. Tokheim and Johnson [8] have determined the optimum axis for thermal compensation. Sato and Carter [9] have developed a method for rapid alignment of YIG spheres to the optimum axis.

The planar YIG technology is not so far advanced. The temperature characteristics of prototype oscillators have been considered, however. Ishak *et al.* [10] measured the temperature coefficients of MSSW delay-line oscillators. For pure YIG ($4\pi M_s = 1760$ Oe), the temperature coefficient of oscillator frequency was -550 ppm/°C and -210 ppm/°C at 6 and 17 GHz, respectively. For a doped YIG film ($4\pi M_s = 600$ Oe) the temperature coefficient was -500 ppm/°C at 1 GHz. Hartemann [2] reports theoretical calculations of the group delay temperature dependence for MSSW and MSFVW based on the temperature dependence of the saturation magnetization of pure YIG. The theory agrees substantially with the data of Ishak *et al.* for the MSWDLO. The theoretical temperature coefficient of the frequency sensitivity is almost three times larger and of opposite sign for the MSFVW as compared to the MSSW. This agrees with the data reported by Adam [11] for a narrow-band MSFVW delay line at 7.58 GHz. Adam used the temperature coefficient of rare earth cobalt bias magnets for compensation, reducing the temperature coefficient to $+4$ ppm/°C. The most likely temperature stabilization schemes for MSW devices will probably be based on Adam's technique, although differential temperature coefficients of soft magnetic materials in the magnet structure could be used also.

It should be pointed out that these temperature stabilization schemes for MSW devices are not fully developed and are essentially narrowband in nature. A more general approach would be to use an oven for temperature stabilization, as is done for stable YIG sphere applications, or to adjust the magnetic field with a trimming coil under microprocessor control.

IV. Oscillator Phase-Noise Characteristics

The theoretical basis for the phase noise of a two-port resonator or delay-line-based oscillator has been the subject of much discussion for the SAW case, and this theory is applicable to the MSW case. We shall present some aspects of a summary of this theory by Henaff [12]. In Fig. 4, a model of a typical resonator or delay-line-based oscillator phase-noise spectrum is shown. Typically, as many as four straight line segments appear on a plot of the log noise power versus log of frequency offset from carrier. Each is of the form f^{-n}, where $n = 0, 1, 2, 3$, for the noise floor, flicker phase noise, white frequency noise, and flicker frequency noise portions of the spectrum, respectively. The corners occur at $f_0/2Q$ for a noise power of G^2kTN and at $1/\tau_0$. The oscillator frequency is f_0, Q is the quality factor of the resonator, G^2 is the power gain of the feedback amplifier, F is the noise figure, kT is -174 dBm, and τ_0 is determined by power supply, components, and temperature instabilities [12]. The f^{-2} portion of the spectral density S of the phase-noise spectrum can be expressed as

$$[S_\phi(f)]_{-2} = \frac{kTFG^2 f_0^2}{2P_0 Q^2 f^2} \quad (1)$$

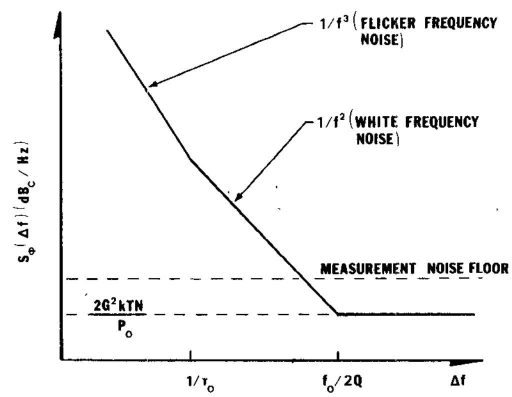

Fig. 4. Phase-noise model.

where F is the noise figure of the amplifier and P_0 is the loop power at the amplifier output. This white frequency noise may be interpreted as the (resonator) filtered broadband noise referred to the input of the amplifier. The parameter N is not necessarily the spot noise at f_0. As pointed out by Pucel [13], considerable baseband noise can be mixed in as a result of the nonlinear amplifier saturation processes. Consequently, GaAs FET's typically exhibit poorer phase-noise performance in an oscillator than bipolar devices due to the excessive "$1/f$" noise of the GaAs FET.

Equation (1) suggests a characteristic figure of merit R_c for the efficacy of a resonator in a feedback oscillator

$$R_c = 20 \log \frac{Q}{f_0 \mathrm{GHz}} - \mathrm{IL} \quad (2)$$

where IL is the resonator (or delay-line) insertion loss. For a delay line

$$R_c = 20 \log \pi \, \tau \mathrm{ns} - \mathrm{IL}. \quad (3)$$

Thus, the single sideband phase noise is

$$L(\Delta f) = R_c - P_0 + F - 20 \log \Delta f. \quad (4)$$

Equations (2)–(4) apply to the f^{-2} ((1))noise only.

We now routinely make matched MSSW resonators at UTA with $R_c = 35$ dB from 3 to 6 GHz. These resonators are typically fabricated using 1-mm×25-mm×15-μm YIG films and an array spacing optimized for $\lambda = 300$ μm. For a loop power of 10 dBm (the high-frequency saturation threshold for MSSW), F = 5 dB, and an oscillator output of 0 dBm, this would correspond to L (10 kHz) $= -120$ dBc/Hz.

In Fig. 5, the measured phase noise is plotted as a function of frequency offset from the carrier for four oscillators. The data for the HP 11729B is included for comparison to a synthesized frequency source. The UTA data was taken using a two-stage GaAs FET amplifier, a 1-mm×25-mm×15-μm MSSW resonator with $Q = 1600$ and IL = 15 dB at 5.4 GHz and with $\lambda = 300$ μm ($R_c = 34$ dB, $P_0 = 6$ dB). Castera *et al.* [14] used a four-stage GaAs FET amplifier and a 25-mm×25-mm×23-μm MSFVW resonator with $Q = 800$, IL = 18 dB at 5.0 GHz ($R_c = 26$ dB). Ishak *et al.* used a MSSW delay line with $\tau = 180$ ns at 5.5 GHz ($R_c \leqslant 49$). The values of R_c given are for

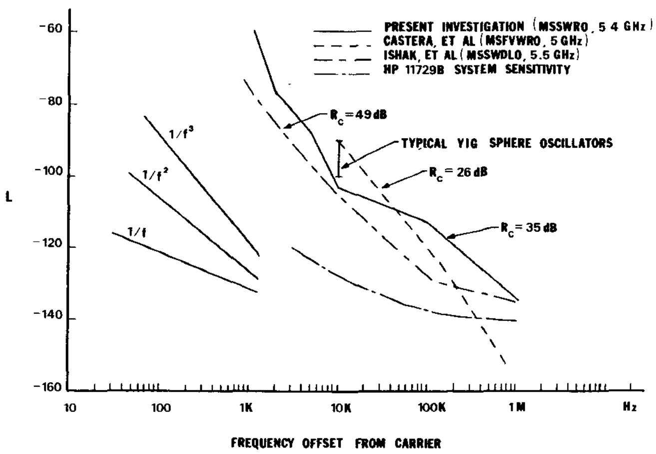

Fig. 5. Phase noise of MSW oscillators.

frequency offsets of 10 kHz from the carrier and properly indicate the order of the experimentally measured phase noise at 10-kHz offset. Since the data of Castera *et al.* follows an f^{-3} slope, the system flicker noise overpowered the f^2 noise completely. This may be a characteristic of the MSFVW oscillators. The data reported for the MSWDLO and MSSWRO both show a region of f^{-2} noise at 10-kHz offset. The MSWDLO is close to optimum, as will be shown later, but improvements in amplifier noise figure should yield even better than the -105 dBc shown here.

The MSSWRO is at least 20 dB from the optimum for a resonator, so this data should be improved as the learning curve is advanced. In both MSSW cases, the planar YIG oscillators have exceeded the phase-noise performance of the YIG sphere oscillators (typical values at 10-kHz offset are shown in Fig. 4). The material-limited phase noise can be computed for both the MSSW resonator and delay-line oscillators by using the Gilbert model approach of Vittoria and Wilsey [15]. The optimum value for the figure of merit R_c can be computed. We will optimize the quantity

$$\frac{Q_m}{f} \times \text{material loss} = \pi\tau e^{-\alpha V_g \tau} \qquad (5)$$

since Q (delay line) $= \pi f \tau$. Note that for a given delay (i.e, essentially the physical length) a resonator will have a Q of $(1-\rho^2)^{-1}$ greater than the delay line where ρ is the array reflectivity. Equation (5) is optimized for a delay of

$$\tau_{\text{opt}} = (\alpha V_g)^{-1}.$$

The optimization of delay-line length for broad-band operation will be the subject of a future paper. Using the theory of Vittoria and Wilsey [15] we tabulate values of τ_{opt} and R_c^{opt} for MSWDLO's made of material of various

TABLE I.
OPTIMIZED VALUES OF DELAY AND OSCILLATOR FIGURE OF MERIT FOR VARIOUS VALUES OF LINE WIDTH

ΔH(Oe)	τ_{opt}(nsec)	R_c^{opt}(dB)
0.15	758	59
0.30	379	53
0.50	227	48
1.00	114	42

FMR line widths. The corresponding values of R^{opt} for a resonator would be larger by a factor of $-20 \log (1-\rho^2) \gg +3$ dB. Transducer IL will, of course, reduce R_c in either case. The data in Table I indicates that by optimization of the MSWDLO reported by [10] Ishak, an improvement of 5–10 dB in phase noise (thus approaching -120 dBc/Hz can be achieved by using low line-width material.

V. SUMMARY

A comparison of YIG sphere and planar resonators has shown that the planar configuration has great promise both in ease of fabrication and in potential superior performance. The planar resonant elements offer a better electrical match to typical gain elements and already have surpassed the spheres in phase-noise performance, with additional improvement theoretically available. The temperature performance of the planar devices is not as elegantly optimized as for the spheres, but can be accomplished.

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