NEW APPLICATIONS OF NARROW-LINEWIDTH POLYCRYSTALLINE CaVG’s TO MS-MODE ANALOGUE DELAY LINE, MS-MODE-SUPPRESSED FERRI-MAGNETIC RESONATOR, AND NEAR INFRARED FARADAY ROTATOR

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NEW APPLICATIONS OF NARROW-LINEWIDTH POLYCRYSTALLINE CaVG's TO MS-MODE ANALOGUE DELAY LINE, MS-MODE-SUPPRESSED FERRI-MAGNETIC RESONATOR, AND NEAR INFRARED FARADAY ROTATOR

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Résumé. — On décrit les recherches effectuées dans le laboratoire des auteurs qui sont consacrées aux applications des grenats de type CaV — utilisés à la place des grenats monocristallins habituels — aux dispositifs suivants : 1) circulateurs à très faibles pertes, 2) résonateurs gyromagnétiques, 3) correcteurs de phase à mode magnétostatique et 4) modulateurs magnéto-optiques dans l'infrarouge. On insiste d'une part sur la suppression et le contrôle des modes magnétostatiques parasites et d'autre part sur la correction de phase à hautes performances ajustable électroniquement, telle qu'elle est appliquée dans les dispositifs 2 et 3. Quant au dispositif 4, qui est une application des études orientées vers les ferrites micro-ondes, on montre que certains grenats de CaV ont des performances magnéto-optiques comparables dans l'infrarouge à celles des grenats monocristallins.

Abstract. — Device-oriented researches under way in author's laboratory are outline which are devoted to the applications of the narrow-linewidth polycrystalline CaVG's as a class of replacement of the familiar single crystalline garnets, to (1) extremely low-loss circulators, (2) gyromagnetic resonators, (3) MS-mode phase correctors, and (4) the infrared magneto-optical modulator. Emphasis is placed upon the suppression and control of the unwanted MS-modes and a highly efficient electronically adjustable transversely biased phase corrector as to the items (2) and (3), respectively. Concerning the item (4) an outgrowth from the microwave-ferrite-oriented studies, some of the CaVG's are demonstrated to be comparable with the single crystalline garnets in the infrared magneto-optical performances.

1. Introductory remarks. — About half a decade after its independent advent by S. Geller et al. [1] primarily aimed at the cost reduction of the microwave garnet materials through the elimination of the costly Yttrium, the family of Ca-V substituted YIG, hereafter referred to as CaVG, provoked a serious interest among both the microwave engineers and physical researchers concerned with the gyromagnetic relaxation with their linewidths (Δf) reduced to as narrow as 2 (Oe) at X-band, of the proportion of single-crystals, in a polycrystalline form.

Since then, intensive studies were conducted by independent research groups at Raytheon Research Lab. [2], Philips Tech. Lab. [3], Marconi Company [4], Thomson-CSF Company [5], and NEC and Matsushita Company of Japan [6], [7], with a particular emphasis on interpretations of the relaxation mechanisms and thereupon based tailoring of the firing and sintering processes to lower relaxations. Noteworthy was the fact that the effective linewidth was resorted to as a logical and powerful measure of the biasing field dependent relaxation, which, in turn, is dictated by the porosity, the anisotropy, the impurity and other secondary factors remaining to be identified.

In 1974, T. Inui demonstrated, in a series of studies following those quoted above [6], that such a process that causes the grain size to be increased to somewhere around 400 microns may be realized, thus reducing the linewidth (Note: In view of the measuring procedure, this may be termed more accurately as the effective linewidth.) down to 2 (Oe) just below, and far above, the critical frequency defined as (2/3) γ(4πMs)/2 π [8].

The reference [8], contained another noteworthy finding that, when a particular process was employed to increase the grain size to about 400 microns with due attention paid to reduce the porosity and anisotropy, some polycrystalline samples of CaVG behaved much like the single crystalline YIG's in the sense that the linewidth spectra as measured over a wide range of 0.5 GHz to 5 GHz were not associated with any eminient peak at and around the critical frequency, in distinction to the existing polycrystalline garnet materials.

Prompted by this finding, the present authors launched a series of R. & D. works specifically designed for replacing the single crystalline garnet with the polycrystalline CaVG, thereby to reduce the cost as well as to enhance the practicability in (1) Extremely
Low-loss Circulator, (2) Gyromagnetic Tuning Elements for Swept Signal Sources, (3) MS-mode Tunable Microwave Phase Correctors, and (4) Infrared Magneto-optical Modulators.

Following are descriptions on the recent achievements and progresses pertaining to the above-mentioned items.

2. Microwave properties of CaVG's and relevant measuring devices. — It will be appropriate to start the descriptions with briefing the measurements relevant to the microwave behaviour of the polycrystalline CaVG's on hand. These include the linewidth spectra over 0.5 GHz to 5 GHz, measurements of $\mu_+^*$ and $\mu_-^*$ far off the resonance field, and measurements of dispersion and absorption in the resonant region.

Figures 1 (a) through (c) show some typical plots of the magnetic linewidth (W) spectra for grain sizes 14, 20, and 460 μm, respectively (1). As has already been depicted, the definite peak at the critical frequency in the sense of the spin wave state density vanishes for 460 μm, implying the single-crystal-like behaviour of this particular specimen [8,9]. Measurements have invariably been carried out by using a non-resonant method [10] wherein the specimen mount functions as a class of single-stage band-rejection filter (2).

Turning to such practical applications as conventional circulators and non-reciprocal phasors, ferrites are required to have as large a value of $(\mu'_+ - \mu'_-)$ or $(\mu'_+ - \mu'_-)/(\mu'_+ + \mu'_-)$ as possible with as small a value of $(\mu'_+ + \mu'_-) \times (1/2)$ as possible under the biasing field actually applied.

Fig. 1. — Effective linewidth spectra of the narrow linewidth polycrystalline CaVG's for three different grain sizes. Noteworthy is that the sample C, with a grain size of 460 μm and a saturation magnetization of 1 300 gauss is free of the linewidth peak at the critical angular frequency given as $(2/3) (\gamma 4 \pi M_s)$ as shown in (C), in distinction to the samples, A and B, with grain sizes, 14 μm and 20 μm, respectively, and saturation magnetizations respectively of 1 130 and 1 100 gauss, as shown in (A) and (B).
Assessment in terms of the above-mentioned parameters starts with an experimental determination of \( \mu_+ \) and \( \mu_- \) under the practical biasing status. Figures 2 (a) through (c) show measurements of \( \mu_+ \) and \( \mu_- \) far above the gyromagnetically resonant region, with samples machined to a shape of cylindrical column from the same batches as those for figures 1 (a) through (c). In carrying out the measurements, a specifically designed and fabricated cylindrical TB\( \text{II} \) mode resonator was used, which was filled with an axially biased sample and excited simultaneously in a circularly polarized mode of the positive sense and in that of the negative sense, in such a physical configuration as shown in figure 3 [9].

As is evident from the figure, the filling factor is raised to unity, enabling \( \mu_\text{eff} \) to be measured as accurate as to \( 2 \times 10^{-4} \) as implied by figures 1 (a) through (c), by means of a simple conventional swept signal technique [9].

Further plots have been made of \( (\mu'_+ + \mu'_-)/2 \) as a function of \( (\mu'_+ - \mu'_-)/(\mu'_+ - \mu'_-) \) to correlate the microwave loss for a range of practical biasing fields with the linewidth (\( W \)) spectra as depicted above [9]. Plots obtained for grain sizes, 14 \( \mu \), 20 \( \mu \) and 460 \( \mu \) are reproduced in figure 4, which clearly indicates that the larger the grain size is, the lower is the loss under practical biasing fields.

Finally, in the ferrimagnetically resonant region, use has been made of a microwave ferromagnetic spectroscope [11] specifically designed for recording both the absorption and the dispersion curves as a function of biasing magnetic field, literally at a fixed measuring frequency, in our case at 3.880 GHz, so as to be free of any dispersion-caused error even for such narrow line-width as 5 (Oe) or so associated with the narrow line-width CaVG’s on hand.

This capability was embodied in a form of a varactor-tuned sample cavity resonator which permanently incorporates at an appropriate position a specifically selected varactor or voltage-variable capacitor, which functions both as a wobbulator and as a fine tuner so as to tune the sample cavity invariably to the source frequency say, 3.88 GHz [11].

3. Replacement of single-crystalline YIG with polycrystalline CaVG for extremely low loss circulators. — Pre-requisite to the practical implementation of the uncooled parametric amplifier is a class of extremely low-loss circulators operated at room temperature, which was fabricated successfully of the single-crystalline YIG several years ago [10]. One of the logical actions to be prompted by such data as shown in figure 4 will be to replace this single crystalline garnet material with some of the narrow linewidth CaVG’s.

The above-mentioned replacement has in part been substantiated [12] in a form of the conventional stripline Y-circulator comprising a pair of ferrite discs normally biased, gaining typical performance data as listed in the fifth row of table I, which also includes, for the comparison purpose, the data for a single-crystalline garnet and a conventional YAlIG, all of the same saturation magnetisation as that of CaVG. According to this list, the quoted narrow-linewidth CaVG polycrystalline garnet allows to realize an insertion loss of somewhere around 0.12 dB inclusive of the losses of connectors and matching sections, which is only 0.02 dB higher than that available by the single-crystalline YIG but 0.07 dB
Assessment of narrow-linewidth polycrystalline CaVG in terms of the performance data for stripline circulator in comparison with those of single crystalline YAlIG and polycrystalline YAlIG. All three circulators are specifically designed and optimized to a VSWR of less than 1.07 over 3.7 to 4.2 GHz, for an identical saturation magnetization of 1200 (gauss).

<table>
<thead>
<tr>
<th>Ferrite</th>
<th>$4\pi M_s$ (gauss)</th>
<th>$\Delta H$ (Oersted)</th>
<th>$\tan \delta e$</th>
<th>Dimensions (mm)</th>
<th>Biasing magnetic field (Oersted)</th>
<th>Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow linewidth CaVG</td>
<td>1.200</td>
<td>2.2</td>
<td>$\leq 5 \times 10^{-4}$</td>
<td>$10 \varnothing \times 2.8 \tau$</td>
<td>350</td>
<td>$0.11 \leq 0.13$</td>
</tr>
<tr>
<td>(Polycrystal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YAlIG</td>
<td>1.200</td>
<td>2</td>
<td>-</td>
<td>$13 \varnothing \times 3.0 \tau$</td>
<td>690</td>
<td>$0.10 \leq 0.10$</td>
</tr>
<tr>
<td>(Single crystal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YAlIG</td>
<td>1.200</td>
<td>50</td>
<td>$\leq 3 \times 10^{-2}$</td>
<td>$13 \varnothing \times 3.0 \tau$</td>
<td>690</td>
<td>$0.18 \leq 0.23$</td>
</tr>
<tr>
<td>(Polycrystal)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

lower than that available by the conventional YAlIG for a saturation magnetization of 1200 gauss over a relative 20 dB bandwidth of 12% centered at 4 GHz, with respective biasing fields optimized to best performances. This finding implies that the polycrystalline CaVG's include those which lend themselves to a cost-effective design and fabrication of the parametric amplifier circulators.

4. MS-Mode suppressed gyromagnetic resonators. —
For some time, the narrow-linewidth polycrystalline CaVG's have been finding uses for tunable circuits incorporated into the electronically swept experimental microwave signal sources over a frequency range, 0.5 GHz to 1.5 GHz, mostly in a form of small thin disc [10][13], as well as over the X-band in a form of small sphere [14]. As is well acknowledged the former shape or the thin disc sample is in general sensitive to the unwanted MS-mode excitation, thereby exerting deleterious influences on the uniform-mode-based operations. This subsection is devoted specifically to the description of approaches to, and achievements in, the unwanted mode suppression.

Our step taken to fulfil this objective is to apply some classes of selective perturbations to the unwanted MS-modes, thereby to damp out or shift the spectra [11].

Figure 5 shows one of the MS-mode spectra inclusive of the uniform mode as recorded on a disc-shaped sample of the polycrystalline CaVG. In the above-mentioned attempt to shift the unwanted MS-mode spectra, a partial metallization was applied either on one or on both of the top and the bottom surfaces of the sample to differing extents. The effect of this partial metallization is demonstrated in figure 6.

**FIG. 5.** A pair of absorption and dispersion curves as automatically recorded on a narrow-linewidth polycrystalline CaVG disc utilizing the 4 GHz fixed frequency gyromagnetic spectroscope.

**FIG. 6.** A pair of absorption and dispersion curves as automatically recorded on a disc sample of the same origin as that for figure 5 but metallized by gold at top and bottom surfaces.
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The measured spectrum in figure 6 demonstrates the effectiveness of the partial metallization in suppressing the unwanted MS-modes. However, to our regret, the uniform mode is also observed to undergo the perturbation to some extent, say, an increment of $\Delta H$ of somewhere around 5 (Oe).

As an alternative to the metallization, a ferromagnetic perturbation has also been applied in a form of non-microwave MnZn ferrite discs as glued on either one or both of the top and bottom surfaces of CaVG disc. One of the spectra as measured on this class of sample is reproduced in figure 7, which shows that the situation is much like that for the metallized disc, in that the unwanted MS-modes are suppressed at a price of a $\Delta H$ increment of about 5 (Oe) at 3.88 GHz.

Summarizing the above-mentioned findings, the proposed perturbational measure has been demonstrated to be effective to suppress the unwanted MS-modes on the disc sample, even if at a cost of the resonance linewidth being extended by a few oersteds, which remains to be alleviated through further elaborations of perturbers in both the pattern and the material.

5. Analogue MS-mode phase corrector. — A few years ago, J. D. Adams et al. made a proposition of a class of analogue phase corrector [15] utilizing the surface MS-mode propagated on the epitaxial YIG film, giving rise to a renewed interest in the MS-mode as a potential candidate for novel analogue magnetically-tunable devices. If embodied by using the polycrystalline materials, these devices are certain to feature practicabilities furthered, costs reduced drastically and an ease with which complex configurations may be machined, all due to the polycrystallinity.

In realising the MS-mode phase corrector made of the narrow-linewidth bulk of polycrystalline garnet, a scheme of transverse biasing was resorted to, giving such a configuration as shown in the companion paper [16].

This structure propagates both the surface and the volume MS-modes of which our choice based on the measurement of attenuation is the latter. As to be detailed in the companion paper [16] the experimental phase corrector has been measured to feature such $\tau_\phi$ vs. frequency performance as shown in figure 9 for insertion losses nearly of the same proportion as those of single-crystalline versions [15].

6. Infrared magneto-optical modulator. — The final subject matter is concerned with whether or not the narrow-linewidth polycrystalline CaVG's are capable of replacing the single-crystalline YIG's for the magneto-optical infrared Faraday rotator and modulator with their single-crystal-like behaviour.
as has been demonstrated at least in the microwave region.

In the first place, a family of CaVG samples with differing grain sizes was measured with respective samples shaped in a disc measuring 5 mm in diameter and 1, 2 or 3 mm in thickness on the commercially available infrared spectroscope. Some of the measurements are shown in figures 10 and 11. The former figure including the preceding achievements indicates that the narrow-linewidth polycrystalline CaVG

features an attenuation considerably higher than that of the single-crystalline YIG [17], but about two orders of magnitude less than that of polycrystalline YIG [18] and of the same of order of magnitude as that of the single crystalline BiCaVG [19].

The latter figure, 11, shows attenuation spectra for differing grain sizes. As far as the indicated family of plots is concerned, no definite correlation is found between the grain size and attenuation, in distinction to the situation in the microwave frequency range, implying that much remains to be examined for a satisfactory elucidation.

The material screening in terms of the attenuation spectra was followed by a series of tests based on the Faraday rotation. CaVG samples were shaped in a cylindrical puck, polished on surface to an optical flatness, and installed on a Faraday rotation test assembly with a modulation coil wound around in a configuration much like that due to R. W. Cooper et al. [20] as shown in figure 12, to measure the Faraday rotation angle or the modulation degree as well as the overall insertion loss [21]. This test assembly used a mechanically chopped ray as an amplitude reference.

In figures 13 (a) and (b), reproduced are the scope displays of a 1 kHz modulation current and a detected infrared output signal for a Faraday rotator made of a single-crystalline YIG puck and that also of a puck of the above-mentioned polycrystalline CaVG with the minimal loss, respectively, with the measuring wavelength set to 1.37 μm, the analyser set at 45° relative to the polariser, and respective samples machined to dimensions as indicated in legends.
The Faraday rotator comprising the polycrystalline CaVG puck has been measured on the above-mentioned test assembly to feature a modulation degree of 33% for a modulation frequency of 1 kHz and a modulation power of 0.53 W as compared with 50% for the single crystalline YIG. The insertion losses have been measured to be 1.4 dB and 2.5 dB respectively for the single-crystalline YIG and the polycrystalline CaVG pucks. Of these two figures, about 1.3 dB is contributed by the surface reflection, thus making the difference of overall losses less eminent between the single crystalline YIG and the polycrystalline CaVG, at least, in the absence of the anti-reflection coating.

7. **Concluding remarks.** — Above-mentioned experimental demonstrations and measured data will be enough to imply a potential capability of the class of narrow-linewidth polycrystalline CaVG’s of replacing the familiar class of single-crystalline YIG’s in some practically important gyromagnetic devices for lower costs and for an ease of fabrications, although much remains to be done in both the physical interpretation and the device fabrication.

Thanks are due to Mr. Kitazume of Nippon Electric Company for his willingness to incorporate the family of CaVG’s of interest into the practical circulators on production.

References