Microwave Ferrites: the Present and the Future

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Abstract. The state of the art of microwave ferrite technology in Russia is reviewed. The paper gives some generalization with respect to the future progress in the field, where the one of major tasks is likely to be a development of specialized gyromagnetics for mm- and sub-mm-range devices.

1. INTRODUCTION

The present state of the art and trends in development of microwave ferrites in Russia are shown via analysis of characteristic properties of those materials and parameters of microwave devices achieved by R & P "Domain" Company - the leading company of former USSR in ferrite field.

2. WHERE WE ARE AND FUTURE TASKS

Among the numerous classes and types of soft magnetic materials the microwave ferrites (MWFs) occupy a special place. Of all the world-wide production of soft ferrites the MWFs account for some 0.02% by tonnage (50 metric tons annually) and retain about 1% of sales volume. But the average price of microwave ferrite parts is more than 50 times higher than that of similar (by weight) MnZn or NiZn ferrite cores which are synthesized in an alike fabrication process. There is a certain delusion that such a difference in prices is due to high cost of rare-earth oxides, the main ingredient of magnetic garnets. It is true to some extent only. The cost of row materials for microwave garnets does not exceed in most cases 15% of the product selling price. The reasons behind the high prices of MWFs as compared with conventional low-frequency ferrites are (a) considerable number of parameters to be held to close tolerances and liable to in-process tests; (b) more complicated precision sintering schedule with respect to homogeneity of heating field, strict temperature maintenance, and close control of atmosphere in furnace;(c) exacting requirements to purity of initial materials for MWFs fabrication.

Despite the relatively low output of MWFs throughout the world, the number of their existing grades exceeds one hundred and is still growing. This fact owes both to wide diversity of requirements to suit to certain types of ferrite devices and to working frequency band of each particular model. As an example, in table 1, some microwave devices of our company are shown. They present the current level of achievements in Russia. These devices were designed with the use of MWFs of our own that provided characteristics of devices close to today's limits.

A. From items 1 and 10 it is seen the practical possibility to use polycrystalline YIG in development of devices for 3 MHz to 300 GHz range. Moreover, 300 GHz region is not the upper limit for use of these materials. In our research works, there has been developed an experimental model of Faraday rotation switch/circulator for work at frequencies of about 600 GHz. For that prototype, a hot-pressed garnet SG-178-1 ($4\pi M_S$=1780 G, ΔH=25 Oe) was used. In 10 percent frequency band it demonstrates 5,5 dB of insertion loss and 10 dB of isolation. We believe the high limit of frequency range for that class of devices to be at least 1 THz. Above that limit, a behavior of ferrite is little-studied. Approximate estimates show that, in the range of 1 to 10 THz, one could expect an occurrence of relaxation absorption maxima due to a spin exchange interaction resonance in ferrite.

B. Items 7 and 8 demonstrate the ability of ferrites to withstand record-high levels of microwave signals power: tens of kilowatts of average power and tens of megawatts in a peak. There are already the models of waveguide isolators for hundreds of kilowatts of average power. We firmly believe that isolators and circulators can be designed with existing MWFs

Table 1

Microwave Ferrite Devices of R&P "Domain" Co. (S.P.A. "Ferrite"), St.Petersburg, Russia

Item, No	Model	Type of ferrite used	Main characteristics			
			Frequency range	Ins. loss/ Isolation	P_{av}, W/ P_{puls}, kW	Dimensions, mm
1	0FCB50-2 coaxial tuned filter	polycrystal YIG	**3÷7 MHz**	3.0/50	1/1	69×97×56
2	4FWS62-2 waveguide tuned filter	**hexaferrite** single crystal	**50÷75 GHz**	8.0/37	0.01/	**55×55×60**
3	1CCS27-1 **coaxial** circulator	polycrystal YIG	**24÷31 MHz**	0.9/17	700/1.0	420×400×105
4	4ICS18-1 **coaxial** isolator	polycrystal YIG	**17.7÷19.7 GHz**	0.5/20	1.0/	13×16×10
5	2IMS28-1 **microstrip** isolator	polycrystal YIG	**0.26÷0.31 GHz**	0.7/18	60/	50×32×17
6	4IMM94-1 **microstrip** isolator	**hexaferrite** polycrystal	**93÷94 GHz**	1.6/18	0.1/	1×7×**0.11**
7	3CWP21-1 waveguide circulator	polycrystal spinel	1.7÷2.6 GHz	0.9/24	**22 000/36 000**	1470×425×310
8	3CWN60-1 waveguide circulator	polycrystal YIG	4.9÷7.05 GHz	**0.07**/30	100/	100×95×58
9	4IWU35-5 **waveguide** isolator*)	polycrystal spinel	33÷37 GHz	1.5/20	**3000/300**	1500×400×480
10	5SWY32-1 **waveguide** switch-circulator**)	polycrystal YIG	**(325±10) GHz**	**2.5**/16	**1.0**/10	150×60×60

Notes: *) Overmoded waveguide, 40 mm in diameter
**) Overmoded waveguide, 7×7 mm

for any power level of microwave sources available today. Different versions of device design to control the level of permissible working power in a wide range are still far from being exhausted.

C. Item 8 is a circulator. Its very low level of insertion loss (0.07 dB) provided by using a serial YIG, points to the fact that similar devices for other frequency ranges can also be designed matching the loss already achieved. It is significant that there is no exact quantitative correlation between static characteristic properties of MWFs ($4\pi M_S$, ΔH, ΔH_k, $tg\delta_\varepsilon$ et al.) and working parameters (α, R, Δf) of a particular ferrite device being developed for a specific frequency range. Mostly, operational characteristics of such a device would be determined by its physical design. Optimization of characteristics is usually being achieved experimentally, and final choice of optimal design is always limited from time and money viewpoint.

D. Items 2 and 6 show benefits of using hexaferrites in development of mm-wave devices. The main advantage of these models is their small size that is attainable either by sharp decrease of external beasing field (Item 2) or through abandonment of it at all (Item 6). The latter is feasible only in some points of mm-wave range because of discrete values of anisotropy field of existing ferrites (Table 2). In development of MWFs, it is important to provide the close cooperation between ferrite technologists and electronics engineers. Such a complex approach enabled "Domain" to solve the main task of manufacturer - to provide the products being competitive on world market. You can judge this by the properties of microwave devices (Table 1) and microwave ferrites (Tables 2, 3). Bold-faced figures present the today's level of our achievements.

Let me give you some comments to materials listed in Tables 2 and 3.

Group 1 - polycrystalline garnets with narrow gyromagnetic resonance linewidth (ΔH). On the whole, their characteristics are on a par with that of similar material grades of Trans-Tech Corp., leading, to my mind, in the market,.

Group 2 - polycrystalline garnets for high power devices. It is necessary to note that, in this case, relatively narrow ΔH is accompanied by relatively wide ΔH_k. The latter value defines a threshold level of spin wave excitation effected by large amplitudes of microwave signal.

Group 3 - polycrystalline spinels which provide combination of narrow ΔH (narrow enough for spinels) with wide ΔH_k, as well as with relatively low dielectric losses and high squareness of hysteresis loop.

Group 4 - polycrystalline hexaferrites characterized by a wide spectrum (from 11 to 33 kOe) of anisotropy fields (H_A), relatively low dielectric loss and physical density close to Roentgen one. The latter feature is especially important for mm-wave devices to be manufactured by hybrid-integral technology.

Table 3 presents garnets, spinels and hexaferrite single crystals. As a good achievement in garnets, we consider the narrow ΔH in the broad line of material grades with $4\pi M_S$ value from 90 G to 1850 G. As for spinels and hexaferrites, they display ΔH rather narrow for these types of crystalline structures.

The level of achieved characteristics of both MWFs and microwave devices, though rather high for today, is still far from physical limits or from attainable values, at least. The next decade progress in that field should go through resolving the problems related to further expansion into the region of mm and sub-mm waves. Advantages of this wavelength range over

Table 2

Polycrystalline Microwave Ferrites

Group of materials, Grade	$4\pi M_S$, G	ΔH, Oe	ΔH_K, Oe	$tg\,\delta_\varepsilon$ $\times 10^4$	T_K, °C
1.ΔH-narrow YIG					
NG-52					
NG-103	520	**10**	1.5	**2**	120
NG-160	1030	**10**	1.0	**2**	170
NG-190	1600	**12**	1.0	**2**	225
	1900	**15**	1.0	**2**	215
2.High-power YIG					
SG-47					
SG-85	470	**45**	**19**	**2**	130
SG-120	850	**45**	**10**	**2**	210
SG-178-1	1200	**30**	**10**	**2**	220
	1780	**25**	**6**	**2**	280
3.Spinels					
1CCH-9-G	5000	**110**	**12**	**4**	**345**
4CCH-10-G	2300	**110**	**35**	**5**	**500**
1CCH-11[1]	4750	**250**		**6**	**450**
4CCH-14B[2]	1550	**350**		**5**	**390**
4.Hexaferrites					
HD-11[3]	3700	2500		10	510
HD-20[4]	2400	2000		10	400
HD-28[5]	2100	1500		10	270
HD-33[6]	1700	1500		10	240

[1),2)] $B_r/B_m=0.9$
[3)] $H_A=11$ kOe, $d=4.9$ g/cm^3
[4)] $H_A=20$ kOe, $d=4.9$ g/cm^3
[5)] $H_A=28$ kOe, $d=4.95$ g/cm^3
[6)] $H_A=33$ kOe, $d=4.95$ g/cm^3

Table 3

Single-crystalline Microwave Ferrites

Group of materials, Grade	$4\pi M_S$, G	ΔH_{min}, Oe	f_{test}, GHz	T_C, °C	F_{lim}, GHz
1.Garnets					
8KG	**90**	**0.5**	0.5	100	0.2
12KG	**140**	**0.5**	0.7	120	0.4
15KG	**200**	**0.4**	1.0	140	0.5
25KG	**300**	**0.4**	1.0	150	0.7
30KG	**350**	**0.3**	1.0	155	0.8
35KG	**430**	**0.3**	1.0	150	0.9
50KG	**620**	**0.3**	1.5	220	1.3
65KG	**820**	**0.3**	2.0	160	1.7
120KG	**1500**	**0.3**	9.0	260	3.2
140KG	**1750**	**0.2**	9.0	280	4.0
150KG	**1850**	**0.3**	9.0	225	4.2
2.Spinels					
180KSH	2300	**2.5**	9.0	500	3.8
290KSH	3600	**2.0**	9.0	670	4.7
360KSH	4500	**2.0**	9.0	530	9.2
3.Hexaferrites					
8KB*)	4520	**35**	50	395	36
14KB**)	4700	**25**	50	450	53

*) $H_A=11$ kOe
**) $H_A=17$ kOe

cm and longer waves are very practical. They provide: (a) increased resolution and noise immunity of radars; (b) elimination of atmosphere hindrances (dust, mist, rain, clouds, etc.) in the operation of short-range radar and telecom systems, what is unattainable with the use of infrared and optical technique; (c) significant decrease of material and power consumption of transceiving instruments. In spite of these attractive advantages of mm-waves, development of microwave technology for this range was being performed with much lower rate compared with that of cm- and dm-waves. It's not my intent to go into various problems of mm-wave technology development. I will only go into detail on related problems with respect to mm-wave ferrites. The Nature had managed in such a way that the cm-wave range proved to be the most favorable one for the use of microwave ferrites. Their properties manifest themselves there with the most effect. In the region of lower frequencies, some problems arise that caused by a notable influence of additional loss mechanism related to natural gyromagnetic resonance in ferrites. There are two methods of lowering that negative effect:

1. By the choice of ferrite having the lowest possible values both of saturation magnetization and effective anisotropy field (H_A). However, this approach entails decrease of effective Q-factor of ferrite device, which is the increasing function of saturation magnetization.
2. By transition from traditional design of isolators and circulators with below-resonance bias field to devices functioning beyond resonance. But this results in a size increase of external magnetic system.

Getting into the mm-wave region, we come up against other problems. The most critical ones are as follows.

1. The size of external magnet system in resonance devi-ces operational over 30 GHz is practically unacceptable.
2. In devices working with low biasing fields, gyromagnetic activity of ferrites, characterized by non-diagonal component "K" of r.f. magnetic susceptibility tensor, is being decreased inversely to operational frequency:

$$|K| = \gamma \cdot \frac{4\pi M_S}{f} \qquad (1)$$

where $4\pi M_S$ - saturation magnetization of ferrite, f - operational frequency, $\gamma=2.8$ MHz/Oe - gyromagnetic factor.

Let me consider some ways to resolve these problems.

A. Resonance devices.

Obviously in this type of devices (tuned filters, limiters, etc.) garnets and spinels, slightly anisotropic by their nature, have physical limits for using over 50 GHz. However, there are alternative materials for the same application. They are magnetic substances with high dielectric properties, which have a "gap" (Δf) in zero-point external field in the spectrum of resonance (in frequency vs magnetic field domain to be more exact). For example, hexaferrites and antiferromagnetics have this property (Fig.1). The value of frequency "gap" in magnetouniaxial hexaferrite magnetized in parallel to anisotropy axis is defined as

$$\Delta f_1 = \gamma H_A \qquad (2)$$

An advantage of hexaferrites, which allows one to use in mm-wave devices small-volume biasing magnets, if any, is well known. But up to date, they did not find a wide application in mentioned devices. I suppose that the main

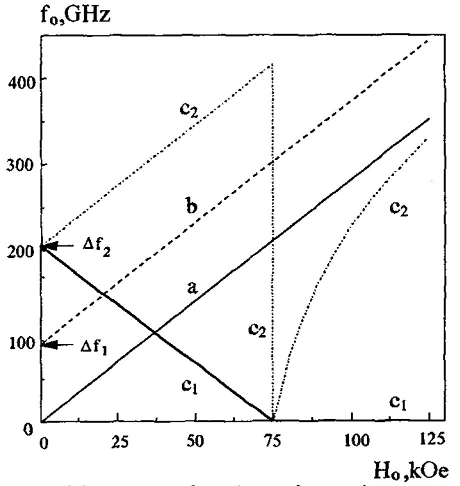

Fig.1. Field-frequency dependence of magnetic resonance in materials of different crystal structures.
a - "Isotropic" garnet
b - Magnetouniaxial hexaferrite (H_A=33 kOe)
c_i - Magnetouniaxial antiferromagnetic α-Fe_2O_3 (H_C=75 kOe)

reason fot this is an inadequate investment in development of that technology being rather complicated but promising.

The same words can be said about realization of very efficient and scientifically substantiated idea to use new class of magnetic materials - antiferromagnetics - in resonance devices. They are mostly the simple oxides and salts of transition metals. The value of frequency "gap" in magnetouniaxial antiferromagnetics magnetized in parallel to anisotropy axis is defined by:

$$\Delta f_2 = \gamma (2H_E \cdot H_A)^{1/2} \quad (3)$$

where H_E - effective field of intersublattice spin exchange interaction. Heller et al. [1] and Voronkov [2] have shown possibilities of creation of non-reciprocal resonance devices on the basis of single-crystalline antiferromagnetics Cr_2O_3 [1] and α-Fe_2O_3 [2] for frequency range from 180 to 210 GHz. But, those experiments have not received further development mostly because of obvious technical complexity of would-be devices which need cooling down to liquid nitrogen temperature (77 K). The practical use of antiferromagne-tics in resonance mm-wave devices is conditioned by the success in development of materials with narrow linewidth of antiferromagnetic resonance (ΔH_{AFMR}) and high values of magnetic order (T_N).

B. Non-resonance mm-wave ferrite devices (phase, Y- and T-circulators, isolators and switches).

For this type of devices, the main problem in achievement of the level of parameters comparable with that of cm-wave devices is the upper limit of saturation magnetization of existing microwave ferrites, which does not exceed 5200 G. Hence, gyromagnetic activity decreases as frequency goes up resulting in a decrease of both bandwidth and Q-factor of devices. There are strong grounds to believe that search of new composition of MWFs with $4\pi M_S$ over 6000 G among traditional crystal structures (garnets, spinels, hexaferrites) is hopeless. The effort in development of these devices, especially for the shortest mm waves, should be based on either new physical concepts or the use of radically new gyromagnetic materials.

C. Faraday rotation devices.

Microwave devices based on Faraday rotation effect are the most perspective models from the viewpoint of effective use of MWFs in non-reciprocal designs at mm and sub-mm waves. This is due to fundamental character of Faraday effect: independence of polarization plane turning angle (φ) on frequency in infinite gyrotropic medium:

$$\varphi / l = \frac{1}{c} \gamma 4\pi M \sqrt{\varepsilon} \quad (4)$$

where c - velocity of light, ε - dielectric permittivity of medium, l - path length of wave.

Comparing equations (4) and (1) shows the obvious advantage of Faraday devices over phase-type models in mm-wave range. That was well proved in practice. At present, number of companies in the USA and Europe produce ferrite Faraday-type isolators and circulators for frequency up to 220 GHz. However, when frequency increases, insertion loss in device grows significantly. That can be explained, first, by increase of "electrical length" of ferrite element, needed to obtain the given value of rotating angle, say, 45 degrees. The second reason is growing losses by the length with increasing frequency in standard one-mode waveguide. For first reason, it is nothing to do with it because it is inherent to the essence of Faraday rotation effect. But the influence of second reason can be diminished, first by using overmoded waveguides of enlarged cross-section for transmission line and, second, by going to the engineering quasi-optical type of devices. The good example of the latters is the switch/circulator (Table 1, Item 10) operating at 325 GHz with insertion loss of 2.5 dB.

In conclusion, recent microwave ferrites meet the present requirements and demands of system designers with the exception of those who deal with ferrite devices for mm wave range. In the nearest decade one can expect a significant progress in the technology of synthesis of new gyromagnetic materials for applications in mm and sub-mm wave ranges.

Acknowledgments

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Dr Alex GOLDMAN

is awarded the TAKESHI TAKEI PRIZE for 1996...

During the opening of the ICF 7 banquet in Saint-Emilion, the TAKEISHI TAKEI PRIZE for 1996 was awarded to Dr Alex GOLDMAN, in recognition of his contribution in the field of ferrite technology and materials.

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Dr Alex Goldman received his M.A. and Ph.D. degrees in physical chemistry from Columbia University.

Since 1987, he is president of Ferrite Technology Worldwide (Pittsburg, Pennsylvania, USA) an international consultant firm in ferrite research, manufacturing and applications.

Previous to that time, he was Corporate Director of Research of Spang and Co and its Magnetics Division. His major technical involvement there was in microwave ferrites, single crystal growth of garnets, coprecipitation of ferrites and magnetooptics in garnets.

Dr Goldman is the author of « Modern Ferrite Technology » (Van Nostrand Reihnold, 1992) and he is preparing a « Handbook of Modern Ferromagnetic Materials » (Chapman Hall, 1997).

He has contributed chapters on ferrites and other magnetic materials in various books: « Modern Electrical and Electronic Engineering » (John Wiley, 1986), « Encyclopedia of Material Science and Engineering » (Pergamon, 1992), « Electronic Ceramics, Properties, Devices and Applications » (Marcel Dekker, 1988), « Engineered Materials Handbook », vol.4 (ASM, 1991), « Encyclopedia of Advanced Materials » (Pergamon, 1995), and with B.B. Ghates « Material Science and Technology » (VCH, 1992).

He has authored numerous technical papers and is the holder of 5 patents on ferrites.

He was co-chairman of the 4th ICF held in San-Francisco in 1984, and is an honorary member of the ICF International Advisory Committee. He is a life member of the Institute of Electrical and Electronic Engineers, of the American Chemical Society and of the American Ceramic Society, of which he is a Fellow.

He has been an Invited Lecturer in several Universities (China, Korea, USA) and scientific institutions (IEEE, ACS...).

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At a short ceremony, Dr Patrick Beuzelin of Siemens Matsushita Components asked Professor Sugimoto of Teikyo Heisei University, the recipient of the 1992 Takeshi Takei Prize, to make the presentation of the 1996 ICF 7 Prize.

Acting on behalf of the ICF International Committee and of the ICF 7 Organizing Committee, Professor Sugimoto presented Dr Alex Goldman with a brass and oak commemorative plaque as a token of sincere recognition of his much valued contributions in the field of ferrites.