Microstrip Frequency Doublers Based on a Thin Magnetic Film

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***Abstract*—The article presents the results of measuring the generation of the second harmonic in a microstrip transmission line and in a quarter-wavelength stepped-impedance microstrip resonator with a thin permalloy magnetic film ($Ni_{80}Fe_{20}$). The measurements were carried out for three samples with different thicknesses – 50 nm, 75 nm and 100 nm, at an input signal excitation frequency of 1 GHz and maximum input power of ~3500 mW. It was shown that the level of the second harmonic rises as the TMF thickness increases. It was found that a 100-nm sample generates the second harmonic more efficiently due to the larger ΔH_{FMR} and the larger amount of magnetic material involved in the process of nonlinear conversion of the input power. It was shown that the resonator-based frequency doubler has a conversion factor ~4500 times higher than that of the doubler based on the microstrip line due to the higher value of the loaded Q-factor. Therefore, a quarter-wavelength stepped-impedance microstrip resonator can be used as a frequency doubler.**

Keywords*—*ferromagnetic resonance, frequency doubling, microstrip resonator, thin magnetic film, second harmonic

I. Introduction

Microwave multipliers are currently very widespread in a wide variety of types of electronic equipment. Usually, semiconductors are used as a non-linear element for generating higher harmonics, but in places with high radiation their use is very limited. For this reason, the study of frequency multipliers based on nonlinear elements made of other materials as a nonlinear element is relevant. In particular, magnetic materials have nonlinear properties [1-3] and they are well suited for nonlinear studies and applications [4]. In recent years, thin metallic magnetic films (TMF) have become extremely interesting for use in microwave technology due to their ability to be easily integrated into wafer devices. At the same time, nonlinear effects in permalloy films were studied using stripline transmission lines [5]. Studies have shown that thin magnetic films are applicable for creating frequency multipliers [6].

Currently, two approaches are usually employed to excite nonlinear harmonics in TMFs using microwave fields. The first one is to use a transmission line that is both a generator of an excitation field and a non-linear harmonic detector. The second approach involves the use of a resonator for the same purposes. The main advantage of the latter is that a standing wave is formed in the resonator. The energy stored by the resonator is proportional to its loaded Q-factor. Thus, much more energy will be used to generate the non-linearity in the magnetic medium and most of the energy introduced into the resonator will be used to produce a higher harmonic signal.

It was shown in [7] that a microstrip transmission line containing a thin permalloy magnetic film can be successfully used as a microwave doubler. And in [8], a measurement setup for studying the nonlinear properties of thin magnetic films is described. In both works, a thin magnetic film with a thickness of 100 nm was studied. Thus, it is interesting to study the effect of the thickness of a TMF on the magnitude of second harmonic generation and to compare the frequency doubling efficiency for a microstrip transmission line and a quarter-wavelength microstrip resonator.

II. Theory

The frequency doubling process in magnetic media occurs as a result of the generation of a double-frequency magnetization component along the direction of a static external magnetic field. The equation of motion of the magnetization vector **M** are described by the Landau–Lifshitz equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}^{eff} + \frac{\alpha}{M} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}, \quad (1)$$

where $\mathbf{H}^{eff}$ is an effective field. If an isotropic magnetic material is exposed to a circularly polarized RF-field vector **M** will precess about $\mathbf{H}^{eff}$ at the frequency of the applied excitation field in a circular trajectory. In the case of an anisotropic magnetic material and/or when the excitation RF-field has a linear polarization, vector **M** will oscillate in an elliptical trajectory. In this case, due to the fact that the length of vector **M** is conserved, a nonzero component m_z will appear. In other words, the longitudinal component of the

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magnetization contributes to oscillations at the doubled frequency of the excitation field [9]. Hence it follows that the ellipticity of the precession of the magnetic moment due to the shape anisotropy causes nonlinear effects.

In a second-order approximation, the amplitude of the double frequency component m_z can be expressed as

$$m_z = \frac{1}{4M}\left|m_x^2 - m_y^2\right|, \quad (2)$$

where m_x and m_y are components of the dynamic magnetization determined from the solution of the linearized Landau-Lifshitz equation [10]. It can be seen from (2) why a TMF is very advantageous in terms of excitation of nonlinear harmonics: due to the shape magnetic anisotropy of the shape, the film exhibits a very high of $|m_y|/|m_x|$ ratio. Also, expression (2) shows that frequency doubling in a magnetic material has a quadratic dependence.

III. Automated Measuring System Design and Measurement Methods

For all the measurements of the doubling the frequency of the input signal in the current investigation, we have used a three permalloy (NiFe) thin-films samples. The films were fabricated by dc-magnetron sputtering from $Ni_{80}Fe_{20}$ target. A 5×3×0.5 mm^3 size quartz wafer was used as a magnetic films substrate. An external static magnetic field was applied to create magnetic uniaxial anisotropy in the film plane. The easy axis (EA) of the magnetization was oriented along the long side of the sample. The thickness of the films was about 50 nm, 75 nm and 100 nm.

The following magnetic parameters of the films were obtained using a local spectrometer of ferromagnetic resonance (FMR) at a pumping frequency of 2.5 GHz [11]:
for the 50-nm sample ΔH_{FMR} = 5.5 Oe, M_s = 869.8 emu/cm^3, H_k = 4.15 Oe, θ_k = 179.8°;
for the 75-nm sample ΔH_{FMR} = 6.3 Oe, M_s = 871.2 emu/cm^3, H_k = 4.07 Oe, θ_k = 178.6°;
for the 100-nm sample ΔH_{FMR} = 6.9 Oe, M_s = 881.8 emu/cm^3, H_k = 2.94 Oe, θ_k = 174.3,
where ΔH_{FMR} is FMR linewidth, M_s is the saturation magnetization, H_k is the anisotropy field and θ_k is the angle of the EA orientation with respect to the long side of a sample.

For all the measurements the dedicated experimental setup has been designed. A structure of the experimental setup is shown in Fig. 1. A complete description of the setup is given in [8]. In this work, improvements were made to the measuring setup. First, a stepper motor was used to rotate the Helmholtz coils. All components of the experimental setup were controlled by a computer using a developed MATLAB-based software. These improvements allowed to produce an automate measurement process. Secondly, the microwave isolator (MI) was added. The MI was used to protect the generator from the reflected signal.

Two types of measurement were performed. In the first case, the setup contained a microstrip line, and in the second one - the quarter-wavelength microstrip resonator. In the case of a microstrip transmission line the film was facing the signal conductor. In the case of the resonator the film was facing the ground plane. The microwave signal was purified by BPF2 and contained only the second harmonic component, which was measured by the spectrum analyzer. Additionally, for high-power measurements (>2000 mW) a broadband power amplifier R&S BBA150 was used. A vector network analyzer was used to control the resonator and the filters performance.

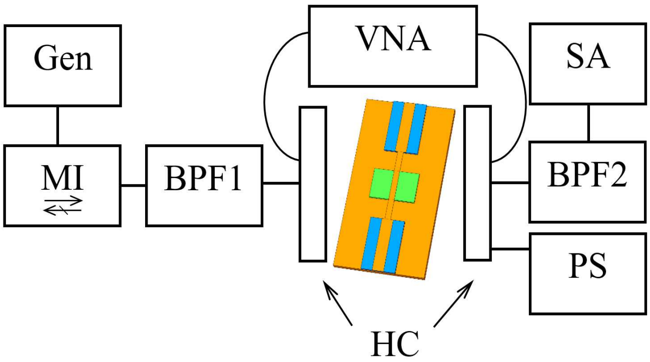

Fig. 1. Measurement setup. HC – Helmholtz coils, PS – power supply GM Instek PSM-6003, VNA – vector network analyzer R&S ZVA50, Gen – microwave generator R&S SMA100B, MI – microwave isolator, BPF1 and BPF2 – bandpass filters, SA – spectrum analyzer R&S FSW

IV. Experiment and Results

The impedance of the microstrip transmission line was 50 Ω. The line consists of three parts. The first and third are located closer to the external ports. A central part of the microstrip line has a structure with an air gap, where a TMF under study is placed below the conductor. A 0.508 mm Rogers RO4003C (ε = 3.38) was used as a dielectric substrate for these segments. The width of line was 1.1 mm. Overall length microstrip line was 30 mm.

Fig. 2 shows the structure of a quarter-wavelength microstrip resonator. The resonator consists of two parts. The first is located closer to the grounded end and has a structure with an air gap, just like the microstrip line. The second part is an irregular microstrip resonator made on a dielectric substrate. The process of modeling such a resonator, its description and tuning are fully described in [8].

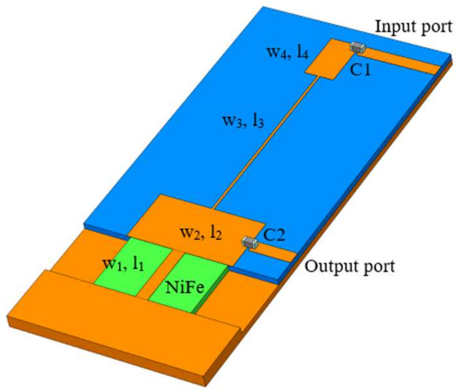

Fig. 2. The resonator structure

The parameters of the resonator for the current study were as follows: w_1 = 1.0 mm, w_2 = 8.75 mm, w_3 = 0.3 mm, w_4 = 2.45 mm, l_1 = 5.1 mm, l_2 = 4.65 mm, l_3 = 15.3 mm, l_4 = 4.1 mm (w is the width and l is the length of the corresponding stripline). The width of feedlines connected to the external ports was 1.1 mm. Rogers RO4003C substrate of ε=3.55 has 0.508 mm thickness The total resonator size was 16.0×35.7 mm^2. During the experiments, the optimal value of the capacitance of SMD components (C1 and C2) 0.5 pF was obtained.

Fig. 3 shows the frequency response of the fabricated resonator with 100-nm-thick TMF. It can be seen that the first resonator oscillation mode is at a frequency of 1 GHz and second resonator oscillation mode is at a frequency of 2 GHz. Moreover, the third oscillation mode is at frequency 6.65 GHz, which indicates that only one nonlinear harmonic is excited in the device. At once a microstrip transmission line has the small transmission and reflection loss in a wideband. In other words, on frequency response of the lines no resonant peaks are observed.

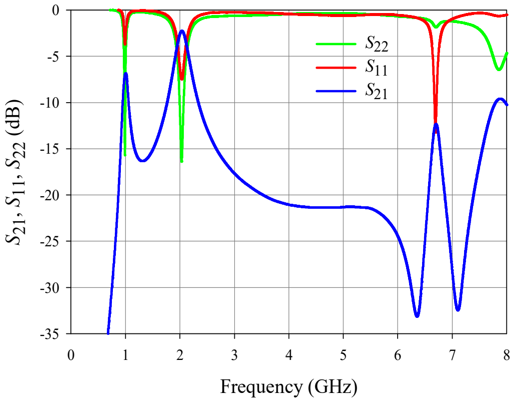

Fig. 3. Frequency characteristic of the quarter-wavelength resonator with a 100-nm-thick permalloy film

As can be seen from the characteristics of the resonator at a frequency of 1 GHz, the transmission coefficient is -7 dB and the loaded Q-factor of the resonator is 10. At the same time the loaded Q-factor of the line is 1. It means that at identical value of input power on the input port the devices the strength of the microwave magnetic field in the resonator will be much higher than in the line.

Fig. 4 shows the angle-magnetic field mapping of the second harmonic generation $P_2(\theta_H, H_0)$ for the resonator with the 100-nm TMF. θ_H is the angle between the excitation field h_{mw} and a static magnetic field H_0. These results were measured for resonator at input signal power 100 mW (at $f_1 = 1$ GHz). The map measurement process was as follows. Using the Helmholtz coils the angle $\theta_H = 0$ was set and the dependence of the output power at the double frequency on the external magnetic field H_0 were measured at this angle value. The value of the external static magnetic field H_0 varied in the range from 1 to 60 Oe. Similar dependencies were measured for each value of the angle θ_H in the range 0…180°. The map demonstrates that there are two maxima of the double frequency signal. The first maximum occurs at $H_0 = 9$ Oe and $\theta_H = 47°$ (the low-field (LF) peak). The second maximum occurs at a higher static field value - at $H_0 = 42$ Oe and $\theta_H = 60°$ (the high-field (HF) peak). Note that for the line, this map looks similar but with a much lower level of the second harmonic. It was shown in [7] that the LF peak is associated with the FMR, while the HF peak occurs due to the modulation of the magnetization by the longitudinal component of the excitation field.

Fig. 4 also shows that at $\theta_H = 0°$ for all values of H_0, there is no generation of the second harmonic. This is explained by the fact that in this case the excitation field is parallel to H_0 and, consequently, parallel to **M**. As a result, the film almost does not absorb energy at the input signal frequency (1 GHz), resulting in a negligible generation at a double frequency. The maximum absorption of the input signal energy by the film

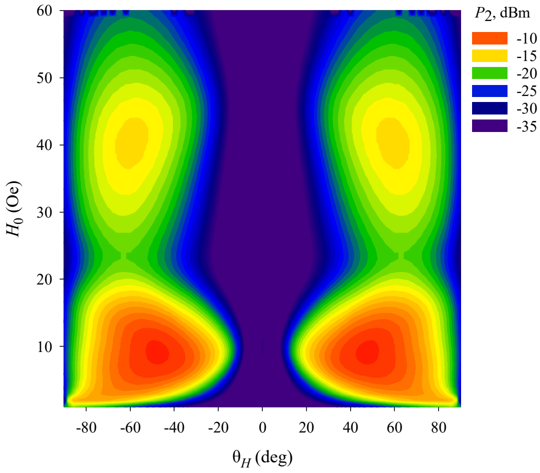

Fig. 4. The angle-magnetic field mapping of the second harmonic generation $P_2(\theta_H, H_0)$ at a double frequency $f_2 = 2$ GHz for sample 100 nm (data obtained for resonator). The input power at 1 GHz was $P_1 = 100$ mW.

will occur when $\theta_H = 90°$. In this case, h_{mw} is perpendicular to **M**, and, for the value of H_0 corresponding to the FMR condition, the imaginary part of the high-frequency magnetic susceptibility of the film is maximum. However, in this case the loaded Q-factor of the resonator significantly decreases due to the strong absorption of microwave power by the TMF. Thus, the optimal angle θ_H at which the output power level at double frequency is maximum is somewhere between 0° and 90°.

In Fig.5 dependencies P_2 for the line and the resonator on the external field H_0 for 100-nm sample are shown. Dependences are obtained from maps (for line and for resonator separately) for optimal values of θ_H at which for a given value of H_0 the power P_2 is maximum. The optimal values of θ_H for each value of H_0 are not the same. Hence it is clearly seen that the LF peak is higher than the HF peak for both the resonator and the line.

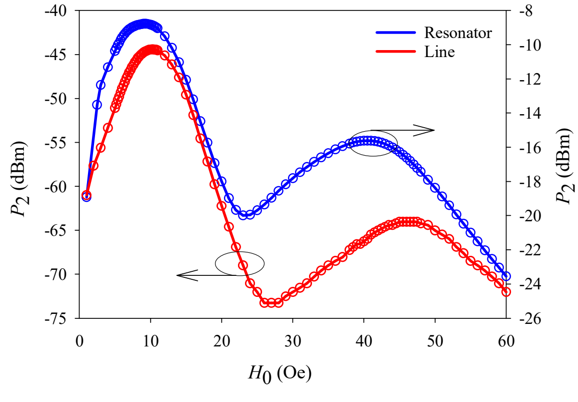

Fig. 5. Dependencies of the P_2 for optimal values of θ_H vs static magnetic field H_0 (in log scale) for line (red curve) and resonator (blue curve). The input power at $f_1 = 1$ GHz was $P_1 = 100$ mW

The ratio of P_2(LF)/P_2(HF) for the line is 45, and for the resonator is 4. This indicates that the LF peak in the resonator is generated less efficiently than in the line. Apparently, the ratio P_2(LF)/P_2(HF) is affected by the strength of the microwave magnetic field generated by the stripline under which the TMF is placed. As mentioned above, for the same input power, the microwave field strength in a resonator will be higher than in the line. It can be seen from Fig. 5 that for $P_1 = 100$ mW the optimal fields H_{opt} for LF and HF peaks for the resonator (H_{opt}(LF) = 9 Oe, H_{opt}(HF) = 42 Oe) are smaller than the optimal fields for the line (H_{opt}(LF) = 10 Oe, H_{opt}(HF) = 47 Oe).

Fig. 6 shows the dependences of the output power level at double frequency (LF and HF peaks) on the input power for the three TMFs of various thickness, obtained for the resonator. For each value of the input power, static magnetic field H_0 and θ_H were chosen from the condition of maximum output power level at double frequency. It can be seen that the level of the second harmonic increases with increasing input power according to a quadratic law for both LF peak and HF peak [7]. At $P_1 = 2000$ mW, P_2 for low-field peak was 5.7 mW, 12.4 mW, and 14.7 mW, and P_2 for high-field peak was 4.6 mW, 7.3 mW, and 10.0 mW for the 50-nm, 75-nm, and 100-nm sample, respectively. For all three samples the maximum generation level is observed for a sample with a thickness of 100 nm. An increase in the TMF thickness leads both to an increase in ΔH_{FMR} and to an increase in the amount of magnetic material involved in the process of nonlinear conversion of the input power, and accordingly to an increase in the second harmonic. It should be noted that for the 50-nm sample, the slope of the transfer characteristic sharply decreases in the region of $P_1 = 1500$ mW. This is due to the fact that the 50-nm sample has the smallest ΔH_{FMR} (among all samples). Therefore, 50-nm sample saturates at a lower input signal power. It should be expected that for 75-nm and 100-nm samples the input power value at which saturation will occur will be higher. For the line, similar dependencies were obtained (with a lower level of the second harmonic).

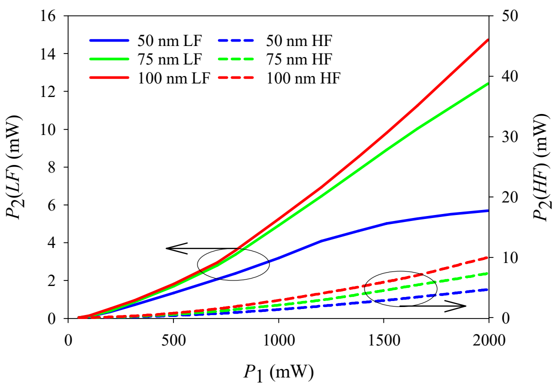

Fig. 6. Level of the second harmonic (low field – solid lines and high field – dashed lines) versus input power for resonator

Fig. 7 shows the dependences of the conversion factor on the input power for 100-nm sample obtained for both the line and the resonator. The maximum conversion factor for the resonator was 0.89% for LF and 0.56% for HF at the input power $P_1 = 3500$ mW. Thus, the conversion efficiency in doubler based on the resonator is 4500-times higher for LF and 26000 for HF than in the doubler based on the line.

V. Conclusion

In this study, three samples of $Ni_{80}Fe_{20}$ thin magnetic permalloy films with various thicknesses: 50 nm, 75 nm and 100 nm were studied. The studies were carried out for the two excitation systems. In the first one, a microstrip line was used as a frequency doubling tool, in the second one – the quarter-wavelength stepped-impedance microstrip resonator was used.

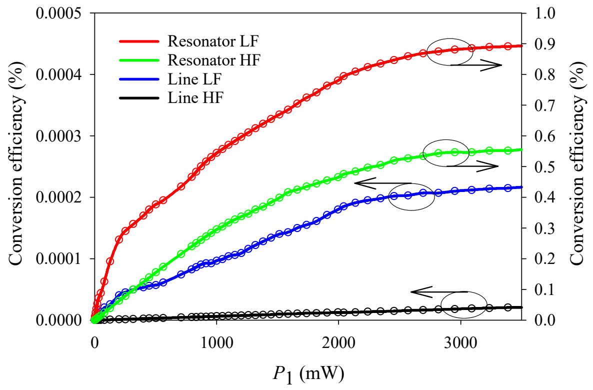

Fig. 7. Level of the second harmonic (low field and high field) versus input power for sample 100 nm for line (blue and black lines) and resonator (red and green lines)

The measurements for the different intensity and directions of the external static magnetic field detected two peaks in the generation of the second harmonic: low-field and high-field peaks. In the current configuration it was found that LF peak is higher than HF peak for both excitation schemes.

The measurements made it possible to evaluate an influence of the film thickness on the second harmonic generation level. The studies have shown that an increase in the thickness of TMF leads to an increase in the level of the second harmonic, for both the resonator and the line.

The maximum conversion factor for the resonator was 0.89% at the input power $P_1 = 3500$ mW, which is 4500 times higher than the conversion factor of the microstrip line. So it means that the quarter-wavelength stepped-impedance microstrip resonator is perspective for its use as a frequency doubler. The microstrip line is still a good instrument for studying the influence of the TMF parameters on the second harmonic generation.

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