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Operation Analysis of a Novel Concept of RF Source Known as Gyromagnetic Line

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***Abstract*— Gyromagnetic nonlinear transmission lines are interesting new devices used for RF generation since they are all solid state, lightweight and compact, neither requiring vacuum nor thermionic filament as in electronic tubes. Experiments with these lines have demonstrated their successful operation at L and S bands, thereby enabling them for applications in UWB pulsed radars in space vehicles and defense systems. There is also a great interest in compact solid-state high-power microwave sources for applications in small defense platforms (boats, trucks, etc.) to destroy the enemy electronic systems. Although the operation of these devices has been demonstrated exhaustively in recent years, their working principle is not quite well understood so far as it has been expected that the precession of the magnetic dipoles in the ferrite material given by the Larmor frequency, which predicts a proportional increase with the magnetic field bias. However, as observed experimentally the opposite occurs and the frequency decreases with the increasing of the magnetic field applied. Thus, the objective of this paper is to address this problem using the Landau-Lifshitz-Gilbert (LLG) equation with boundary conditions on the TEM mode propagation in the coaxial line. The formulation obtained for the precession frequency will be used to compare with experimental data found in the literature.**

Keywords*— *gyromagnetic effect; transmission lines; magnetic precession; nonlinearity

I. Introduction

Nowadays gyromagnetic nonlinear transmission lines (NLTL) have been studied with great interest [1] since they can generate RF in frequency ranges up to 1-4 GHz at high power (hundreds of MW) as demonstrated recently [2], [3]. Microwaves are induced by the damped gyromagnetic precession of the magnetic moments in the ferromagnetic material as their coaxial structure are loaded with ferrite as a magnetic medium, as shown in Fig. 1. As observed, the gyromagnetic NLTLs strongly depend on the amplitude of the incident pulse and on the static magnetic bias. In fact, this phenomenon can be predicted using the Landau-Lifshitz-Gilbert (LLG) equation [4] from which is obtained that the precession frequency is directly proportional to the effective field, that is the sum of the external field applied and the azimuthal generated by the incident pulse. However, as shown in [5-9] the NLTL performance does not confirm this prediction. In fact, the experimental trend observed indicates that the center frequency decreases with the static axial magnetic field as not expected and increases with the incident input pulse amplitude because of the azimuthal field. A possible explanation for this is that the TEM mode wave propagates down the coaxial line coupled to the azimuthal magnetic field. Then, if the static magnetic bias increases, the rotating azimuthal M field component decreases lowering the frequency of oscillations. On the contrary, if incident pulse increases, the azimuthal M contribution also increases raising the frequency. Thus, the objective of this paper is to address this problem correctly by doing a simplified mathematical analysis using the magnetization equation, i.e. LLG without the damping term, for the TEM mode propagation inside the coaxial gyromagnetic line. With this proper formulation, it will be demonstrated the experimental frequency dependence observed in the gyromagnetic NLTL.

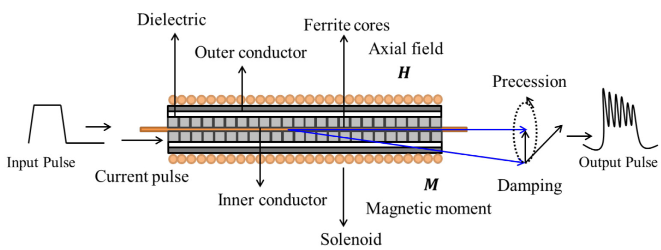

Fig. 1. Gyromagnetic line scheme showing the magnetic precession effect.

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II. MATHEMATICAL ANALYSIS

The principle of operation of the gyromagnetic line is based on the sharpening of the incident pulse rise time along the line. The crest of the wave travels faster than the lower portion of the pulse as the pulse propagation velocity, $v = 1/\sqrt{\varepsilon\mu(I)}$, increases with the decrease of the magnetic permeability because of the application of the high current pulse amplitude. If the line length is sufficiently long, at a certain point on the line the rise time of the high-frequency incident pulse is compressed further and excites the precession oscillation of electron spin moments **S** around the total effective field $\mathbf{H_t}$, composed by sum of the axial external field, azimuthal field induced by the pulse current plus the axial and radial demagnetization fields, which are neglected in our analysis. It is this precession movement of the spins that induces the RF oscillations on the pulse amplitude as it travels along the line. It is assumed that all spins are aligned inside the magnetic material, making together the total magnetization **M** of the ferrite. Thus, under the influence of a total magnetic field $\mathbf{H_t}$, the magnetic moment **M** will tend to align with it but this process is not instantaneous and **M** will precess as a gyroscope whose torque can be given by the magnetization equation as:

$$T = \frac{1}{\gamma}\frac{\partial \vec{M}}{\partial t} = \mu_0 \vec{M} \times \vec{H}_t \qquad (1)$$

where $\gamma = 1.76$ T/rad.s is the electron gyromagnetic ratio and μ_0 is the free space magnetic permeability. The equation above is the classical form to describe the motion of the magnetization **M** and does not take into consideration the damping movement due to the losses in the ferrite. In fact, the damping term is included in the magnetization equation whose original form was proposed by Landau and Lifshitz in 1935 and later modified by Gilbert (LLG) in 1956 [4] to predict with accuracy the precession movement when damping constant is $\alpha \gg 1$. However, both forms are equivalent if $\alpha \ll 1$, where the known LLG equation is given by

$$\frac{\partial \vec{M}}{\partial t} = \gamma\mu_0 \vec{M} \times \vec{H}_t - \frac{\alpha}{M_s}\vec{M} \times \frac{\partial \vec{M}}{\partial t}, \qquad (2)$$

where M_s is the ferrite static magnetization at saturation. The damping term can be considered torque vector that reduces the precession angle to align the magnetization **M** with the field $\mathbf{H_t}$. However, neglecting the dissipation term in (2) and considering only the first term (the pure magnetization equation) leads to a simpler picture, which is very convenient in the scope of this paper for our mathematical analysis. Thus, when only the dominant z-axial field $H\hat{z}$ is present in the ferrite medium without any interaction with another field, the magnetization equation (2) becomes:

$$\frac{\partial \vec{M}}{\partial t} = \mu_0\gamma \vec{M} \times H\hat{z}\,. \qquad (3)$$

As $\vec{M} = M_x\hat{x} + M_y\hat{y} + M_z\hat{z}$, then the cross product $\vec{M} \times H\hat{z} = -\hat{y}M_xH + \hat{x}M_yH$. Replacing the cross product in (3) and separating partial derivatives in the x and y directions and since $dM_z/dt = 0$ one obtains

$$\frac{dM_x}{dt} = \mu_0\gamma M_y H \qquad (4)$$

$$\frac{dM_y}{dt} = -\mu_0\gamma M_x H. \qquad (5)$$

Since axial field H does not vary with time and is constant, by taking the second derivative of (4) and using (5) or vice-versa a second set of equations is obtained

$$\frac{d^2M_x}{dt^2} + \omega_0^2 M_x = 0 \qquad (7)$$

$$\frac{d^2M_y}{dt^2} + \omega_0^2 M_y = 0 \qquad (8)$$

where $\omega_0 = \mu_0\gamma H$ is the Larmor frequency or precession frequency since this formulation represents the Helmholtz equation in x and y coordinates for the harmonic oscillator.

However, if the ferrite goes to saturation under the application of an intense DC magnetic field **H** applied in the direction z as shown in Fig. 2, the ferrite magnetic permeability to an AC applied field **h** will become anisotropic in the perpendicular x-y plane. Due to the anisotropy observe that the corresponding AC magnetization **m** is not in the same direction with **h** as shown in Fig. 2. Let $\mathbf{M_s}$ be the corresponding static magnetization in the z-direction generated by the field **H**, then magnetization can be written as

$$\frac{\partial \vec{M}}{\partial t} = \mu_0\gamma \vec{M} \times \vec{H}_t = \mu_0\gamma\left(\vec{M}_s + \vec{m}\right) \times \left(\vec{H} + \vec{h}\right). \qquad (9)$$

Since $\vec{M}_s \times \vec{H} = 0$ and neglecting the second small term $\vec{m} \times \vec{h}$ if $\vec{h} \ll \vec{H}$ and $\vec{m} \ll \vec{M}$ then (9) becomes

$$\frac{\partial \vec{M}}{\partial t} = \mu_0\gamma M_s \hat{z} \times \vec{h} - \mu_0\gamma H \hat{z} \times \vec{m}\ . \qquad (10)$$

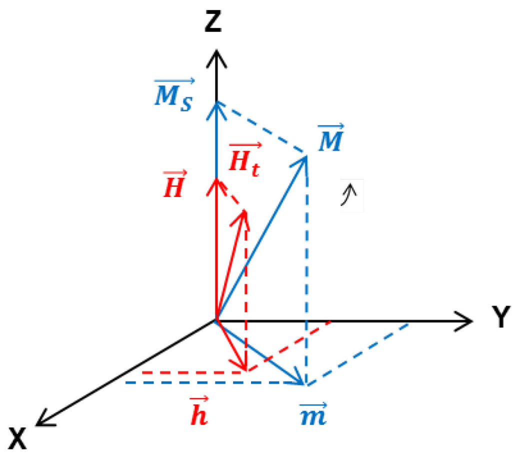

Fig. 2. The rotating total magnetization M around z caused by the AC field h applied.

Separating the components of the fields in coordinates x, y and z, and assuming temporal dependence in the form of $e^{j\omega t}$ one obtains from (10)

$$j\omega m_x = -\mu_0\gamma M_s h_y + \mu_0\gamma H m_y = -\omega_m h_y + \omega_0 m_y \quad (11)$$

$$j\omega m_y = \mu_0\gamma M_s h_x - \mu_0\gamma H m_x = \omega_m h_x - \omega_0 m_x \quad (12)$$

$$j\omega m_z = 0 \quad (13)$$

where $\omega_m = \mu_0\gamma M_s$ and $\omega_0 = \mu_0\gamma H$. Solving (11) and (12) for m_x and m_y gives

$$m_x = \chi_{xx}h_x + \chi_{xy}h_y \quad (14)$$

$$m_y = \chi_{yx}h_x + \chi_{yy}h_y \quad (15)$$

where

$$\chi_{xx} = \chi_{yy} = \frac{\omega_0\omega_m}{\omega_0^2 - \omega^2} \quad (16)$$

$$\chi_{xy} = -\chi_{yx} = \frac{-j\omega_m\omega}{\omega_0^2 - \omega^2}\,. \quad (17)$$

Thus, the magnetization **m** due to the AC field can be written in the tensor form

$$\vec{m} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \chi_{xx} & \chi_{xy} & 0 \\ \chi_{yx} & \chi_{yy} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} h_x \\ h_y \\ 0 \end{bmatrix} = [\chi](\vec{h}) \quad (18)$$

Now the Polder tensor $[\mu]$ can be calculated using the following relation between AC magnetic induction **B** and the corresponding magnetization **m** added to the static axial bias **H** as

$$\vec{B} = [\mu]\vec{h} = \mu_0\left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + [\chi]\right)\begin{bmatrix} h_x \\ h_y \\ H \end{bmatrix}. \quad (19)$$

Thus, the Polder tensor is found to be

$$[\mu] = \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix} \quad (20)$$

where $\mu = \mu_0(1 + \chi_{xx})$ and $j\kappa = -\mu_0\chi_{xy}$. As noted in the permeability tensor the z component of the AC field has no effect on the axial magnetization as $h_z = 0$ (see (18)). Also, note that $[\mu]$ has a resonance frequency at the Larmor frequency as χ and κ become infinite when $\omega = \omega_0$ (see (16) and (17)) in the ideal case without losses, which means that the energy of the RF field is absorbed by the spins of the ferrite. The precession rotation of magnetization **M** around the axial axis z is defined by the angular frequency ω of the AC field **h**. To check the resonance frequency the axial field **H** can be varied to have $\omega = \omega_0$. This analysis is not new and although very well documented in the literature [10], it is very important to understand the behavior of the RF frequency with the increase of the axial field in gyromagnetic lines. In this case, the analysis in x and y directions of the azimuthal field **h** generated by the pulse current I in Fig. 1 can be linked in a similar way to the magnetization **m** using (11) and (12) in the temporal form as

$$\frac{dm_x}{dt} = -\omega_m h_y + \omega_0 m_y \quad (21)$$

$$\frac{dm_y}{dt} = \omega_m h_x - \omega_0 m_x\;. \quad (22)$$

However, because gyromagnetic lines operate in the TEM mode, the AC magnetic field sees the ferrite as a uniaxial material and then (21) and (22) become:

$$\frac{dm_x}{dt} = -\omega_m\frac{m_y}{\chi_{yy}} + \omega_0 m_y = -\left(\frac{\omega_m}{\chi_{yy}} - \omega_0\right)m_y \quad (23)$$

$$\frac{dm_y}{dt} = \omega_m\frac{m_x}{\chi_{xx}} - \omega_0 m_x = \left(\frac{\omega_m}{\chi_{xx}} - \omega_0\right)m_x \quad (24)$$

where in this case $\chi_{xx} = \chi_{yy} = \chi$ required by the mode symmetry.

By using the second derivative of (23) and (24) as before it is not difficult to obtain again the equation for the harmonic oscillator:

$$\frac{d^2m_x}{dt^2} + \omega_p^2 m_x = 0 \quad (25)$$

$$\frac{d^2m_y}{dt^2} + \omega_p^2 m_y = 0 \quad (26)$$

where the precession angular frequency ω_p is given by

$$\omega_p = \frac{\omega_m}{\chi} - \omega_0\;. \quad (27)$$

From (27) the corresponding precession frequency is

$$f = \frac{\gamma}{2\pi}\left(\frac{\mu_0}{\chi}M_s - \mu_0 H\right) \quad (28)$$

where, in the MKS system, $\gamma/2\pi \cong$ 28 GHz/T, ferrite magnetization at saturation $\mu_0 M_s$ =0.35T, $\mu_0 = 4\pi\times10^{-7}$H/m, H given in A/m, and azimuthal magnetic susceptibility χ is a non-dimensional number that varies with the azimuthal field generated by the line pulse current, which in turn depends on the peak of the input pulse applied.

III. Discussion

The validity of the model proposed can be checked using (28) to compare with the experimental data found in Bragg et al. [5], which gives the precession frequency as a function of the static bias magnetic field at three different input pulse voltage peaks (20, 25 and 30 kV) as shown in Fig. 3. To obtain these experimental results they used a ferrite NiZn NLTL of the order of 1-meter length or less with magnetic axial bias varying between 10-40 kA/m approximately and driven by exciting input pulse voltages between 20-30 kV. The plots of the experimental results show the frequency decrease with the bias axial magnetic field at varying incident pulse magnitudes. However, as expected higher frequency is obtained with higher incident pulse amplitudes as ferrite becomes heavily saturated in the azimuthal direction because of the intensity of the azimuthal magnetic field generated. In Fig. 3, it is also shown the analytic model plotted in magenta given by (28) considering that the magnetic susceptibility decreases to 3 at saturation when an incident pulse is applied. As observed for the experimental results, the theoretical curve shows a linear decrease of frequency with H and, although not perfectly it fits with reasonable accuracy the frequency decay (black curve) for the 20-kV incident pulse amplitude, confirming the value assumed for χ =3.0 at 20 kV. For the 25 and 30 kV cases, in principle a good fitting could be also obtained by decreasing χ in the range of 3.0 – 2.5 as azimuthal magnetic susceptibility drops with higher incident pulse amplitudes. Other important achievement found from (28) is that the gyromagnetic line works well only with high voltage incident pulses because of the need of ferrite saturation in the azimuthal direction. When analyzing (28) the first term becomes much bigger than the second one if χ is small, which occurs if the ferrite saturates in the presence of a high azimuthal magnetic field. By neglecting the second term and if χ decreases to no less than one at ferrite saturation, the maximum expected frequency to be generated from a gyromagnetic line would be of the order of 9.8 GHz (=28GHz/T×0.35T). In principle, this may be a valid affirmative as up to our knowledge gyromagnetic NLTLs reported in the literature have not provided frequencies above 5 GHz yet. This hypothesis is also convincing as χ never reaches zero since ferrite relative magnetic permeability μ_r never drops below 2 or 3 during saturation at most, reminding that $\chi = \mu_r - 1$.

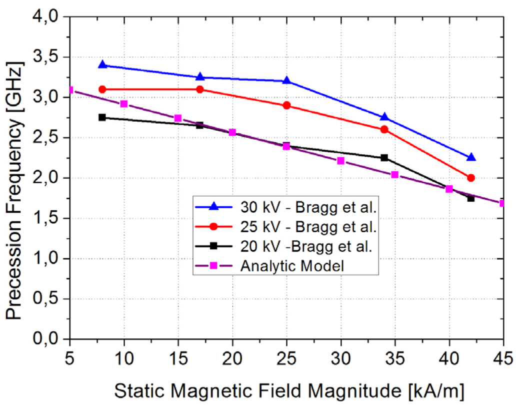

Fig.3. NLTL frequency variation as function of the static axial magnetic field at several incident pulse amplitudes [5] compared to the analytic model developed.

Similarly, Karelin et al. [8] also obtained an almost linear decay of the output frequency versus H using a sophisticated two-dimensional (2-D) model based on the LLG and the Maxwell system of equations in cylindrical coordinates for the TEM wave propagation inside the coaxial line. They tested their NiZn NLTL into a 38 Ω load with an incident pulse amplitude of about 100 kV. By means of a numerical computational method, they have gotten a reasonable fitting between experiment and simulation, which also confirms the validity of their modeling. The small discrepancy observed between their results was due to the ferrite losses not included in their 2-D modeling that provided a frequency variation between 1.7 and 1.2 GHz for the corresponding static fields at 20 and 80 kA/m approximately.

IV. Conclusions

In this paper, we have described an analytic model based on the analysis of LLG equation, which predicts the behavior of a gyromagnetic line in terms of precession frequency variation with the static axial magnetic bias. In contrast to the numerical 2-D model found in [9] ours gives basically the same result, however in a simplified way, i.e. the linear decay of the NLTL frequency with the static magnetic field. Besides, the modeling presented herein is consistent with the earlier experimental results found in the literature [5]. The next phase of the model development is the incorporation of the transmission line telegraphist equations into the model to study the conditions on line parameters to allow propagation of wave oscillations along the line without attenuation.

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