Analysis of a Gyromagnetic Nonlinear Transmission Line Based on Experimental Results

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***Abstract*— Advantages of the continuous non-dispersive lines (also known as gyromagnetic lines) in relation to the discrete nonlinear transmission lines have motivated a deeper study on the first one. Some of these advantages are stronger pulse oscillations at higher frequencies and higher radiofrequency conversion efficiency. Different models have been proposed along the years by several authors with different approaches in order to better understand the gyromagnetic line behavior, using simulation to provide the precession movement. The models already available from other works were studied (including the parameters) by comparison between simulation and numerical analysis techniques. The goal of this paper is to perform the experimental analysis of the gyromagnetic lines previously studied in order to validate the proposed method of analysis. Such a technique could be useful for communications in aerospace systems and/or mobile defense platforms.**

Keywords*— *coaxial line; ferrite beads; gyromagnetic line; magnetic field; NLTL.

I. Introduction

The first investigation on the use of ferrite-loaded lines to obtain pulse sharpening effect was made by Katayev in 1966 [1] using a basic mathematical description. In 1981, Weiner [2] based on Katayev explanations proposed a simplified theory with resistances predicting the output pulse rise time based only on the nonlinear magnetization effect. On the other hand, Pouladian et al. [3] and Pouladian et al. in 1991 [4] showed a complete solution including the ferrite magnetic precession with azimuthal bias, which characterizes the gyromagnetic lines. For this, they used two approaches, where RLC resonant branches were placed in parallel with the capacitors of the model circuit. In the first approach, fixed values were used for the RLC components while in the second approach the values varied along the line gradually. In 2000 Dolan et al. [5] examined a method with instantaneous voltage sources in series with linear inductors to investigate these effects using a numerical program including the presence of an external axial bias to boost the magnetic precession as it induces oscillation along the line which can be used to irradiate RF from an antenna installed at the line output. In summary, several studies with different configurations were proposed in the last decades to investigate the gyromagnetic line, where the more interesting up to date is the one proposed by Dolan et al.[5] as external bias so far is more used to produce RF oscillations at higher efficiencies. In fact, the same results have been obtained by using SPICE simulation (LT) or numerical computation (Mathematica) as given in [6] with good agreement, validating both methods. One interesting aspect of simulations in [6] is that they do not require the use of the voltages sources (nonlinear element) in series with the linear inductor as in Dolan´s model, since the flux equation considers the ferrite magnetization effects. In short, the goal of this paper is to validate the simulated model described in [6] by means of experimental results obtained with a small gyromagnetic line prototype of 20 cm in length.

II. Line Design And Experimental Set-up

The coaxial gyromagnetic line is built by inserting ferrite beads though an internal conductor, where a tape sleeve is used to insulate the ferrite outer surface from the braiding. The first step for the line design is to calculate the saturated inductance in H/m given approximately as [7]:

$$L_i = \frac{\mu_0}{2\pi}\left[ln\left(\frac{do}{di}\right)\right] \tag{1}$$

where $\mu_0 = 4\,\pi \times\, 10^{-7}\text{H/m}$ is the magnetic permeability of free space, do is the outer diameter of the ferrite and di is the inner diameter of the ferrite. Also, assuming ε_r=1 for the ferrite, the linear capacitance in pF/m was calculated as [7]

$$C_0 = \frac{2\pi\,\varepsilon_0}{\ln\left(\frac{do}{di}\right)} \tag{2}$$

where $\varepsilon_0 = 8.854 \times\, 10^{-12}$ F/m is the permittivity of free space. The values used in simulations were based on the

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parameters and dimensions of the ferrite beads, where the line model has to be equivalent to the length of the line (20 cm in this case). For the simulation, the line has to be represented by a large number of LC sections (40). For the line construction, we used Amidon ferrite beads (FB43201) of 3.8 mm in length and with inner and outer diameters of 1.93 and 1.09 mm, respectively. To extend up to 20 cm across the length of the internal copper wire, 53 ferrite beads were placed side by side (see Fig, 1 (a)) and their outer surface isolated from the braiding by two layers of insulating tape, forming a plastic sleeve (Fig. 1 (b)). The braiding was built using a layer of flat metallic solder wire (CT-BRAND) made of copper of 2.5 mm wide (Fig. 1(c)). This setting was kept firmly by welding a thin layer of tin on the cooper braiding (Fig. 1 (d)). To complete the coaxial line construction, two layers of insulating tape were also wound on the outer screening braiding. As line input and output work at high voltages, inner terminals were isolated and kept apart from outer terminals (braiding). The set-up of the experimental gyromagnetic line was completed by placing small pieces of magnets over the extension of the coaxial to produce the magnetic bias axial field.

Fig. 2 gives the scheme employed to test the gyromagnetic line, showing the 50 Ω HV fast pulse generator, diodes and load. The general view of the experimental set-up is shown in Fig. 3. Both signals at input and output were observed and extracted through a 4 kV/250 MHz Agilent probe linked to a 1.0 GHz digital scope from Agilent Technologies. The line was fed by the high voltage pulse generator FPS 5-1 NM, from FID Technology, capable of producing triangular pulses with amplitudes varying in the range of 1.5 kV - 4 kV and with 2.5 ns of rise and fall times. As a testing load, carbon resistors were used because of their small stray inductance as they have solid bulk for conducting the current instead of spiral wires as in the case of metallic resistors with higher inductance. Five power carbon resistors of 10 ohms/3 W were connected in series to provide a 50 Ω load. In order to protect the pulse generator output against reflections a BYW56 diode of 1 kV breakdown reverse voltage was used in series with the gyromagnetic line input. Other five diodes of the same model connected in series at the line output and in parallel with the 50 Ω load carbon resistors were also used as free-wheeling diodes for generator protection.

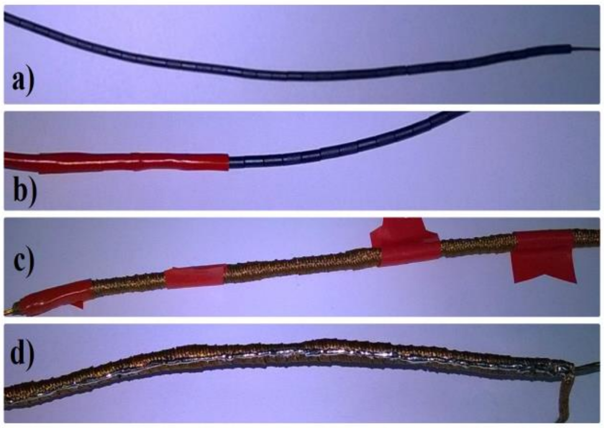

Fig. 1. Construction steps of the coaxial line. a) copper wire inside the ferrite beads, b) insulating tape layer, c) solder wire layer, d) welded tin line.

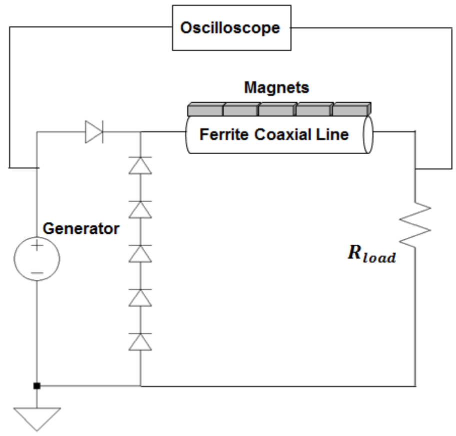

Fig. 2. Squeme employed to test the gyromagnetic line.

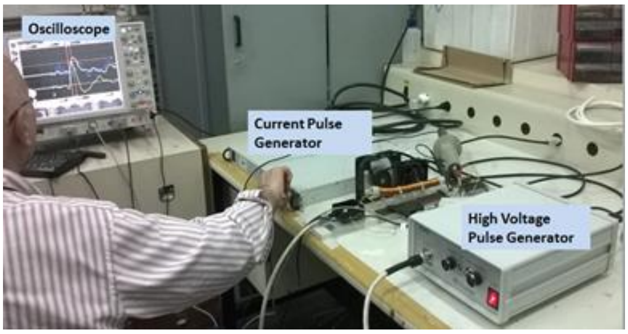

Fig. 3. Set-up used to test the gyromagnetic line.

III. EXPERIMENTAL RESULTS AND SIMULATIONS

Herein the experimental results of the setup-up without and with magnetic axial bias are presented. For magnetic bias, permanent magnets are used and SPICE validation model is tested.

A. *LINE OPERATION WITHOUT MAGNETIC BIAS*

First, Fig. 4 displays the output and input voltages without any magnetic bias, for comparison to the biased cases. In this figure, one can see that there is a line delay of approximately 2.0 ns between pulses as expected and considerable drop of peak amplitude of about 1.6 kV for the output pulse due to the line losses and reflection as the line is not matched to the load because of the nonlinearity.

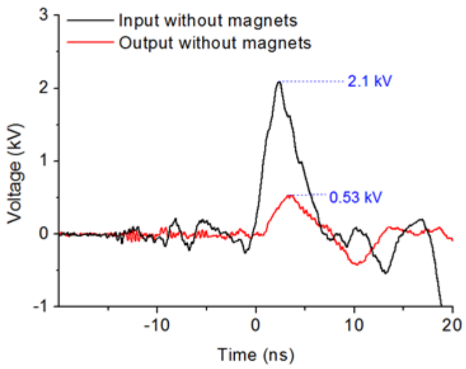

Fig. 4. Input and output of the coaxial line without magnetic bias.

B. *LINE OPERATION WITH PERMANENT MAGNETS*

For line operation with axial magnetic bias without any DC current source, five permanent magnets with transversal square section of 1.5 ×1.5 cm^2 and length of 3.5 cm were placed side by side along the line (on top) as shown in Fig. 5.

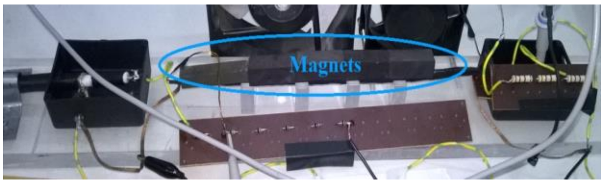

Fig. 5. Several magnets placed along the coaxial line (on top).

Fig. 6 shows the results (input and output pulses) obtained with the set-up given in Fig. 5. It is possible to observe an improvement on the output pulse compared to operation without bias, which demonstrates the considerable magnetization influence on line performance as in this case the output rise time is shortened and the peak amplitude relative to the input is increased.

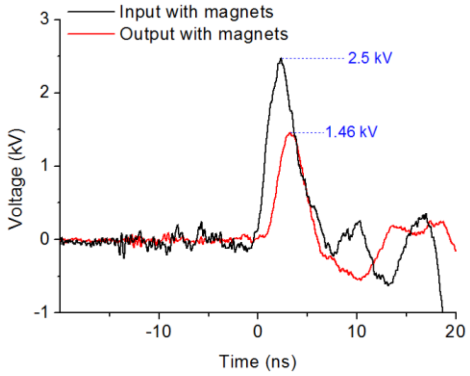

Fig. 6. Input and output pulse using permanent magnets as external bias.

In order to validate the SPICE gyromagnetic simulation described in [6], the circuit model with the same parameters of the coaxial line built and biased with magnets was reproduced (see corresponding scheme in Fig. 7).

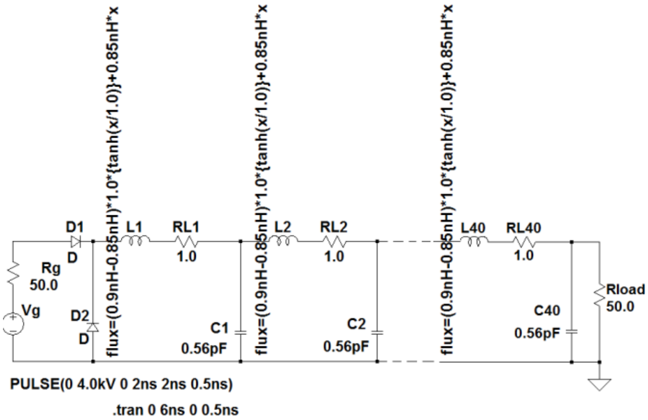

Fig. 7. SPICE scheme used to simulate the gyromagnetic line with magnets.

In the simulation, the generator output impedance and load are fixed at 50 ohms according to the experimental parameters. The input pulse simulated has the same specification according to the experimental result in Fig. 6. The values of the saturated inductance (0.85 nH) and the capacitance (0.56 pF) were calculated according to (1) and (2), based on the ferrite and line dimensions already described. The initial inductance in the flux equation displayed on the schematics was adjusted so that the simulations are fitted to the experimental results since the ferrite magnetic relative permeability (μ_r=160) drops when the permanent magnets are placed along the line. Also, in the scheme of Fig. 7, the resistance of 1.0 Ω in series with the line inductance represents the ferrite losses. A comparison between the experimental results of Fig. 6 and the corresponding simulation scheme in Fig. 7 is given in Fig. 8, showing a good agreement and thus proving the viability of using the SPICE circuit model proposed.

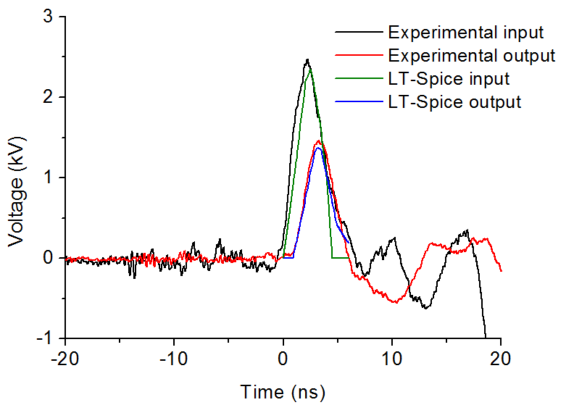

Fig. 8. Comparison between simulations (using squeme of Fig. 7) and experimental results of Fig. 6.

IV. Conclusions

Despite the lack of RF oscillations at the output, the circuit model for gyromagnetic lines was successfully tested, demonstrating the feasibility of the SPICE simulations to assess device performance. Absence of induced oscillations is explained by the use of permanent magnets of low magnetic induction. In future work, this will be addressed by inserting the line into a solenoid coil fed by a DC current source to provide a stronger axial field. Higher input voltages will be also needed to provide a higher azimuthal field due to the pulse current induced and to excite the gyromagnetic effect. SPICE simulation could be used to check the line performance on these conditions to test again model validity for RF generation.

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