State of the Art of Nonlinear Transmission Lines for Applications in High Power Microwaves*

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***Abstract*—Nonlinear transmission lines have been used with great success in pulse sharpening for obtaining output fast pulse rise times in nanosecond and picosecond ranges. Nowadays recent research on this field has shown a great prospect for RF generation using these devices in aerospace application such as in ultra-wide band radar for communications, remote sensing and surveillance due to less attenuation and electromagnetic interference. Also other important applications are envisioned in high power microwave sources for battlefield communication disruption and space vehicle systems as they can replace electronic tubes without the need of vacuum and heating. A nonlinear transmission line basically consists of a lumped LC line using a nonlinear element (variable inductance or capacitance) or a continuous transmission line using a nonlinear medium (ferroelectric or ferrimagnetic). In this paper the state of art for both configurations are discussed as well as their main characteristics and limitations.**

Keywords—transmission lines; nonlinear materials; lumped line; coaxial line; RF generation; gyromagnetic line

I. INTRODUCTION

Recently there has been a growing interest in the study of nonlinear transmission lines (NLTLs) to replace electronic tubes used in high power microwave devices. The reason is that NLTLs can be more compact than TWTs (travelling wave tubes), for instance, as they do not need auxiliary high voltage power supplies, heating filament and vacuum. In view of that, the use of NLTLs presents a great prospect for RF generation applications in space vehicles, satellites, airplanes, mobile defense platforms, etc [1].

The NLTL principle of operation is based on the properties of the nonlinear medium in which the wave propagates. For a nonlinear medium its permittivity ε_r decays with voltage V and as result the propagation wave velocity ($v = 1/\sqrt{(\mu_0\varepsilon_0\varepsilon_r(V)}$, where μ_0 e ε_0 are the free permittivity and permeability) becomes dependent on the input pulse amplitude and the pulse rise time is distorted at the output. However, this effect in NLTLs is explored for output pulse rise time reduction or compression of a flat pump input pulse as the pulse peak travels faster than pulse portions of lower amplitudes during rise time, forming a shock-wave at the output (catch-up effect). This technique is known as pulse sharpening [2-4] and it has been used in applications where it is required short pulse rise times (< 100 ns) as in CO_2 lasers activation [5]. For this technique the transmission line can be a ladder LC transmission line using a nonlinear element L(I) or C(V) or a continuous transmission line using a nonlinear dielectric or magnetic medium. For instance, Fig. 1 shows a lumped LC line with several sections using nonlinear capacitors for the fast rise time shock-wave formation at output. However, since the lumped line is dispersive the minimum achievable pulse rise time at output is limited by Bragg cutoff frequency [2], [6] of the line given by:

$$f_{co} = \frac{1}{\pi\sqrt{LC(V_{\max})}} \qquad (1)$$

where $C(V_{max})$ is the minimum capacitance at the peak voltage.

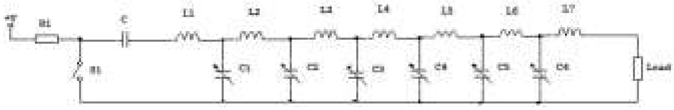

Fig. 1. LC lumped line containing nonlinear capacitors.

For picosecond rise time pulse generation non-dispersive continuous transmission lines [7] are used because in this case the output pulse rise time is only limited by the intrinsic relaxation frequency of the materials employed as nonlinear medium (normally over 1 GHz). Generally due to the strong nonlinearity of magnetic materials the ferromagnetic continuous lines are preferred than dielectric lines as a more effective reduction on the pulse rise time is obtained. Ferrites will reach saturation with their relative permeability drooping from over one thousand to around 2 or 3 while ferroelectric ceramic will have relative permittivity on the order of a few hundred when operating at full working voltage. Fig. 2 shows a coaxial structure for the ferromagnetic line where rings of ferrites are placed aside without air gaps left between them along the internal conductor, which is isolated from the external one by a plastic dielectric of thin thickness. Similar to dielectric materials, the drop in the ferrite relative permeability (μ_r(I)) caused by the applied saturation current will lead to the pulse rise time compression as illustrated in Fig. 2. Nevertheless in the case of using a dielectric line for pulse compression a parallel plate planar geometry is more suitable. This is because in a coaxial line pulse rise time degradation

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would occur as result of the non uniform electric field across the dielectric in this structure [8].

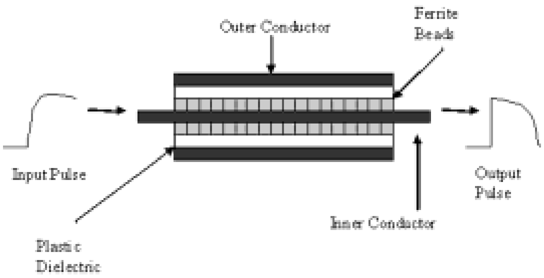

Fig. 2. Ferromagnetic NLTL used for picoseconds pulse compression.

On the other hand, if a flat pump input pulse is injected into a nonlinear dispersive lumped element line LC with a rise time t_{ri} on the order of $1/f_{co}$ the output pulse can be broken into an array of soliton waves [6, 9, 10] superimposed on the maximum amplitude of pump pulse as illustrated in Fig. 3. This phenomenon was observed in the 60's in experiments with pulse compressors for lasers. The explanation for this effect is that line dispersion limits the output pulse rise time t_{ro} to $1/f_{co}$ approximately as energy cannot propagate above low pass filtering line Bragg frequency and the steepness of the output shockwave cannot become infinite. Typical operation center frequency for this train of solitons generated is half the Bragg frequency with a broad bandwidth if a high number of sections of the LC ladder (n>30) is used. Frequency tuning can be achieved by adjusting the applied a DC bias to the nonlinear capacitors or by controlling the small bias current through nonlinear inductors. Also line dispersion can also be controlled by putting additional cross-link capacitors across two inductors in adjacent sections if desired.

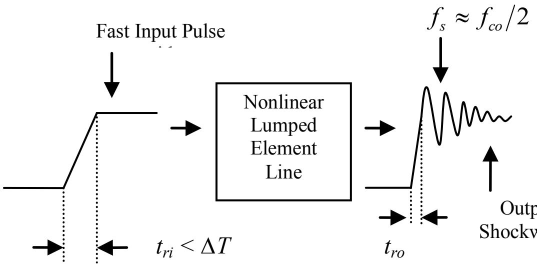

Fig. 3. Illustration of an oscillation burst of solitons produced in a LC ladder.

Other way of producing a RF burst superimposed on a shockwave formed at the output consists of using a ferrite continuous line [11-13], normally employed for pulse sharpening as given in Fig. 2. Ferrite lines with DC bias current flowing across the internal conductor has been used to obtain fast rise times on the order of 1 ns or less. With the improvements of this technique decreased rise times on the order of 300 ps for output pulse amplitudes of 70 kV has been reported [14]. However, when a bar magnet is placed on the ferrites or a solenoid is wound around them the rise time can be decreased very easily from 1ns to less than 300 ps because of external DC magnetic field induced axially [15]. The study of this phenomenon led to the conclusion that the pulse rise time reduction was also related to the excitation of the gyromagnetic mode in the ferrite, i.e. the precession motion of the magnetic dipoles. To present a qualitative view of the process suppose that the dipoles of the ferrites in Fig. 2 are aligned with a DC axial magnetic field H_c pre-applied. As soon as the input voltage pulse is applied to the line the ferrites go into saturation compressing the pulse and reducing its rise time. At the same time, the saturation current generates an azimuthal magnetic field around the internal conductor, which interacts with aligned ferrite dipoles leading to damped precession of the resultant magnetic field with high frequency as shown in Fig. 4. The magnetic field precession [16, 17] is described by the Landau-Lifishitz-Gilbert equation as:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m} \times \vec{H}_c + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} \tag{2}$$

where γ is the electron gyromagnetic ratio, $\vec{H}_c$ is the bias magnetic field vector, $\vec{m}$ is the ferrite magnetization and α is the damping factor that is an intrinsic loaded material property.

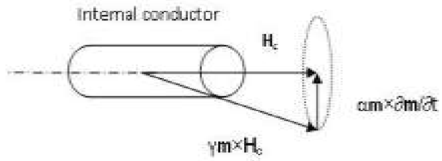

Fig. 4. Mechanism of induced magnetic precession in loaded ferrite lines.

This high frequency precession of the magnetic field induces high frequency voltage oscillations on the front wave of the pulse while it travels along the line. The induced oscillations basically depend on the applied voltage, the bias axial magnetic field, the load and the ferrite material characteristics. Using this mechanism is possible to generate microwave pulses over 1 GHz with power peaks of several hundreds of MW.

II. THE NONLINEAR LUMPED LINE

The history of lumped NLTLs is related the first development of artificial lumped LC lines to achieve pulse compression for radars modulators and lasers during the 50's. In these early days it was observed that besides pulse compression at the modulator output, ringing on the pulse waveform was also formed due to the spread of the frequency components caused by the line dispersion. Only much later it was realized that these oscillations could be used to produce high power RF by controlling line dispersion and nonlinearity [1]. In fact, they are the result of the spreading of the soliton-type waves propagating in a nonlinear medium without changing their shape with velocity that depends on their amplitude. In fact, solitons are waves that were observed for the first time in a shallow water channel in the middle of nineteen century by Scott Russell. Later, in 1895 the mathematicians Kortweg and De-Vries presented a general formulation (called KdV) using hydrodynamics that is the base for the soliton theory. With the advent of computers in the 60/70's, there was growing interest on the study of the soliton propagation phenomena in nonlinear medium. First, this led to the realization of optical soliton generation for applications in optical fibers data transmission and ultra-short pulse lasers. For applications in electronics, varactor diodes were originally used as nonlinear capacitors as in these devices the depletion zone width increases with the voltage applied, which in turn decreases the capacitance associated. Since then many experiments based on capacitive LC lumped lines with varactor diodes and linear inductors have been built to study the soliton generation and propagation [6, 9, 18]. Also these experiments have inspired a lot of applications in modern electronics where the generation of ps pulses is needed, for instance, for oscillators and harmonic generation in microwave range [19, 20]. In this case NLTLs are built using a micro-strips or coplanar waveguides, in which the lines are loaded periodically with varactor or Schottky diodes. This seems to be a good solution for the use of NLTLs in wide band systems, yet only in lower voltage and power applications. Diodes with variable capacitance are generally suitable for low voltages and have been used in NLTLs for shockwave generation with ultra-fast rise rimes in the range of hundreds of picoseconds or in GHz soliton generation, although there are reports on PIN diodes used in production of fast rise time pulses up to 1 kV [1]. And more recently 100 MHz RF production using a NLTL loaded with Schottky diodes of 400 V rated nominal voltage has been also described, but again with low power peak (a few Watts) as the output current obtained is in the range of mA for driving a cold gated emission field cathode [21].

Historically dielectric or capacitive lumped NLTLs (with variable capacitance) have been tried first for RF generation than inductive or magnetic lumped NLTLs (with nonlinear inductance). As said previously, using diodes with variable capacitance in embedded coplanar systems is possible to achieve frequency in the GHz range, but with extremely low power. On the other hand, using commercial ceramic capacitor with great nonlinearity (i.e. of poor capacitance stability) with air core linear inductors is possible to generate RF with moderate frequency and power (10 to 100 MHz and a few kW of power peak) [10, 22]. The same result has been achieved for frequency and power peak using, on the contrary, inductive or magnetic lines made with linear ceramic capacitors and inductors built with windings on ferrite cores [21, 23]. The limitation in frequency for both lines constructed with discrete components has to do with the self-resonant frequency of these devices since this frequency is generally lower than the designed line soliton high frequency. The self-resonant is inherent to the components and depends on the resonance between the capacitance and its associated parasitic inductance for a capacitor, or the inductance and the associated parasitic winding capacitance for an inductor. For nonlinear capacitors the presence of the parasitic inductance is related to several factors: shape, soldering connections and terminal leads, etc. With the voltage limitation, commercial nonlinear ceramic capacitors are normally limited up 3- 5 kV rated voltages. All these limitations cited for dielectric lines were overcome by a pioneer work made by Ikezi et al. [24] in General Atomics in the early 90's when they used parallel plate segmented line inserted with slabs of barium titanate (BT) dielectrics as shown in Fig. 5. Surprisingly they were able to produce soliton generation with power peak of 10 MW with center frequency around 300 MHz below the cutoff or relaxation frequency of the BT used of 400 MHz. Observe in this case that the self resonance of barium titanate tile capacitor must be beyond 500 MHz. Other work that also produced 60 MW of RF using barium titanate tiles in parallel plate transmission line was developed by Brown and Smith [25] at Oxford University in late 90's. At that time they produce lower oscillation frequency on the order of 100 MHz but with higher power peak of 60 MW. Apparently they obtained lower output frequencies because they barium titanate slabs with higher nominal capacitance in the range of nF instead of pF like Ikezi. Anyway, both works indicated that pulses with higher modulation depth can be obtained only using dielectrics of lower losses or with lower equivalent series resistance (ESR) less than 2 Ω [26]. This result was also confirmed by French et al. [27] in 2011 using a segmented line with different dielectric, piezoelectric lead-manganese-niobate (PMN) tiles. In their case, only pulse compression was observed because high dielectric ESR damped all oscillations on the load. Therefore, the search for new dielectrics and designs for use in planar geometry NLTLs are been investigated recently.

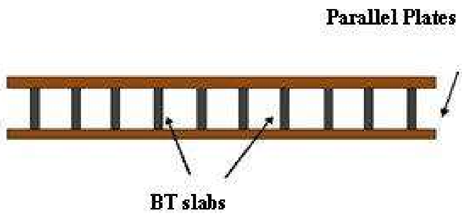

Fig. 5. Parallel plate segmented line used in MHz range.

However, a great breakthrough in 2007 was achieved in terms of maximum operating frequency, pulse power peak and repetition frequency using an inductive line with linear plastic capacitors and magnetic ferrite beads. This was an excellent achievement in contrast with the former soltion source NLTLs made with schottky diodes or barium titanate slabs with linear inductors, which never approached the levels obtained with this new source. In fact, Seddon et al. at BAE Systems [29, 30] developed this new source that was able to produce a train of solitons at an operating frequency between 200 MHz and 1 GHz with power peak of 20 MW under a pulse repetition rate of 1 kHz. The key point for the operation of the system was the heavy saturation of the ferrite and the use cross-link capacitors in the NLTL to increase the dispersion of the NLTL. Also, apparently, in their design the self-resonant frequency of ferrite beads was above the maximum operating frequency as these magnetic materials responded to sub-ns pulses. In their paper the ferrite beads used in the NLTL design was not disclosed as well certain details of project since it is proprietary to BAE. Finally other approach for lumped NLTLs that was proposed in 2008 (Gaudet et al. [1]) suggested the use of LC ladder using both nonlinear element components at the same time for RF generation known as hybrid lines. Actually, this idea was first proposed by Fallside in 1966 [31] for pulse sharpening and later in the 70's Zucker [32] showed theoretically that a higher compression of the output pulse can be obtained by using a hybrid line rather than only an inductive or capacitive line. Other good aspect for this approach is that the load matching problems are minimized in the nonlinear line as line impedance is reasonably kept constant since L and C tends to decrease simultaneously during pulse propagation. Inductive and capacitive nonlinear lines are naturally unmatched systems because of the variation of L or C and, thus RF extraction can be problem in this case due the lower efficiency obtained. Other positive aspect of hybrid lines is that higher operating frequency can be obtained when compared to both conventional inductive and capacitive NLTLs, but at the cost of reduction in the voltage modulation depth of the oscillations as indicated by a previous study [33]. Although some publication is addressing the study of hybrid lines for RF generation in the range of 50- 70 MHz [34], this topic is still an incipient area and many more research has to be done.

III. Nonlinear Gyromagnetic Lines

The use of ferrite loaded coaxial nonlinear for pulse sharpening is an old technique first outlined by Katayev in 1959 [35]. Later, according to Dolan et al. [15] the basis for the operation of the gyromagnetic lines was discovered by chance by D.M. Parker at RSE Malvern, UK, in 1985 when he decided to place a magnet bar around a pulse sharpening ferrite coaxial line. At that time it was observed a pulse rise reduction from 1 ns to less than 300 ps for an output pulse with amplitude of 10 kV. Since then the technique was improved allowing a pulse rise reduction of less than 300 ns with a 70 kV amplitude output pulse [14]. Until early last decade the studies on gyromagnetic lines were concentrated on pulse rise time reduction for pulse sharpening applications taking into account the effect of the magnetic field precession described by the Landau-Lifishitz-Gilbert equation. One important condition for achieving ps fast rise times, besides bead ferrites with sub-ns response and axial magnetic field, was that the gyromagnetic damped factor should be of low value to permit huge pulse rise time reduction. However, as observed in many works [15] a low damped factor induced oscillations on the output sharpened pulse amplitude due to the azimuthal magnetic field precession of the ferrites and later it was realized that these oscillations could be used as a RF source in the same way like the soliton-type generation provided by the lumped nonlinear lines. One of these earlier studies on improving this technology for RF generation was made at BAE Systems, UK, as mentioned by Chadwick et al.[12]. Nevertheless, Rostov et al. [11] were the pioneers in divulgating the results of a similar technology made at High Current Electronics Institute, Tomsk in Russia, by describing a high power nonlinear gyromagnetic line capable of producing RF power peak of 700 MW with central frequency varying between 600 MHz and 1 GHz with efficiency around 10 %. Later in 2011 Chadwick et al. using the same technique produced similar results considering to the central frequency, between 700 MHz and 1 GHz, but with lower RF power peak of about 90 MW [12]. Recently in 2012, Romanchenko et al. [13] from Tomsk reported a 260 MW high power gyromagnetic line operating at a central frequency of 1 GHz with removal of the DC component on the output signal, which was capable of providing a burst of 1000 pulses under a pulse repetition rate (prf) of 200 Hz. In their case, they used RF extraction equipment connected to wideband horn antenna to irradiate, having measured 160 kV/m for the irradiated pulse electric field at 3.5 m distance from the antenna. Other pulsed power group from Texas Tech University has also focused a lot of effort on this technology [16, 17, 36-38] . Recently, they have published several works on temperature dependence of ferrite loaded nonlinear transmission lines as ferrite properties vary greatly with temperature [17, 36, 37]. They investigated the feasibility of gryromanetic ferrite lines operating with permanent magnets instead of solenoids for the ferrites magnetic biasing plus their main parameters and, also the selection of these ferrite beads based on their material compounds (such as MnZn and NiZn) to be loaded in the nonlinear transmission line. At present, they also demonstrate experimentally the possibility of operating NLTLs in range of 2 – 4 GHz with sharpened pulse rise times of 120 ps at extremely prf of the order of 65 MHz with peak power of 5 MW into a 50 ohms load [38], which represents a great breakthrough in terms of prf considering that so far a few kHz was the normal order of magnitude. In view of that, it is expected in future that high power microwave sources maybe provide RF peak power exceeding GWs at a very high prf (probably much higher than 1 kHz) using this technology.

IV. Conclusions

We have seen that that historically NLTLs are related to the techniques developed for pulse sharpening or compression. NLTLs can be lumped or distributed and are made of several shapes and forms such as microstrip, coplanar, coaxial, stripline and parallel plate depending on application, frequency range of operation and output peak power. We have seen as high power microwave sources NLTLs can produce RF in two ways: a) soliton-type generation using a lumped line or b) oscillations generated by the magnetic field precession using a ferrite loaded distributed coaxial line. In principle, dielectric or capacitive lumped lines are more suitable for soliton generation at higher frequencies (> 100 MHz) than their counterparts, inductive or magnetic lumped lines, because their dielectric permittivity varies continuously while permeability of magnetic materials assumes more a square saturation form allied to switching characteristics. For instance, no soliton formation has been reported using segmented magnetic lines as they are not conducive to the dispersion due their strong nonlinearity. However, dielectric losses and material relaxation frequency allied to self-resonant frequency of capacitors have prevented to achieve higher frequencies than 300-400 MHz using these lines. On the contrary, a great breakthrough was achieved when Seddon [29, 30] based on Belyantsev's work [39] introduced cross-link capacitors to raise dispersion and to compensate nonlinearity, inducing soliton formation. The use of ferrite beads with response in sub-ns was also essential in the success for obtaining frequencies in excess of 1 GHz with peak power of tens of MW. Anyway, nowadays gyromagnetic lines appear to be more efficient considering the results described in recent works with frequency reaching several GHz with peak power of tens of MW and efficiencies around 10 %. The trade-offs for using these magnet biased lines are: a) the longer lines compared to unbiased coaxial ferrite lines and b) the use of n external DC with a solenoid on the ferrites to produce the external axial magnetic field required. This latter constraint can be minimized using permanent magnets to keep the system more compact. Also sometimes it is necessary to inject a DC bias current to improve the output waveform, but this introduces the use of more one external supply. Anyway, it appears that lumped lines have a better prospect for use in compact systems rather than gyromagnetic lines that may require DC power sources. Nevertheless, lumped lines, magnetic or dielectric, require more investigation and research to reach frequencies above 2 GHz.

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