ISSN:1983 7402 ITA, 28 a 30 SET de 2016

High-Voltage Soliton Generation with Nonlinear Lumped Varactor Diode Lines

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***Abstract* —In recent years, there has been a great interest in the study of nonlinear transmission lines (NLTLs) for high power soliton RF generation. The easiest way to generate RF based on this effect at low voltages is to use lines built with varying capacitance diodes (varactors). For applications in transmitters of pulsed radars and battlefield disruption systems, higher peak power is required, which can be achieved by operating NLTLs at higher voltages. However, in a high voltage environment because of the lower voltage breakdown of varactors, these devices must be stacked, which causes some constraints on the design of the lumped varactor diode for this application. Therefore, the objective of this paper is to address these issues showing some experimental results obtained with varying capacitance diode (varactor) NLTL prototypes.**

***Key-words* — Nonlinear lines, varactor diode, RF generation.**

I. INTRODUCTION

Nonlinear transmission lines (NLTL) offer a different way of generating RF without using vacuum tubes [1]. They present good prospects for applications in remote sensing, pulsed radar and disruption of battlefield communication. Normally, high voltage (HV) lumped NLTLs based on barium titanate (BT) ceramic capacitors are used for RF generation of soliton packets up to tens of MHz [2-5]. One of the reasons is because suitable BT ceramic capacitors with stronger nonlinearity have a capacitance in the nF range, which limits the oscillation frequency. Alternatively, low voltage (< 30 V) nonlinear lines built with varying capacitance diodes (varactors) with initial capacitance in the pF range have provided soliton production between 100-300 MHz. However, scaling up to HV (> 100 V) by means of a stack with several diodes in series is a problem as oscillations die away if the total capacitance is reduced below a certain value (< 5 pF). It is intuitive that decreasing the capacitance (C) or inductance (L) would increase the frequency, but in practice, the stray C and L will suppress the oscillations [6]. Therefore, in this paper, these issues on frequency limitation are addressed by presenting some experimental results obtained with nonlinear varactor diodes lines. Some considerations on using SiC Schottky diodes [7] of high reverse breakdown voltage to work as varactors in the NLTLs are also discussed.

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Work supported by SOARD/USAF under contract no. FA9550-14-1-0133.

II. NLTL WORKING PRINCIPLE

When an input pulse is injected into a dispersive and nonlinear lumped LC line, it propagates down along the line length with a velocity given by $v = 1/\sqrt{LC}$. For example, in a nonlinear capacitive line, the pulse peak will travel faster than the pulse leading edge of lower amplitude as the capacitance decreases with the applied voltage. The nonlinear capacitance behavior is illustrated by the C×V curve of a varying capacitance diode (BB809 varactor) in Fig.1.

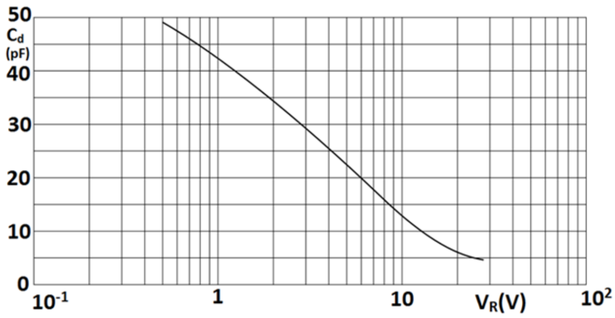

Fig. 1. Typical C×V curve for the BB809 varactor.

In this manner, the pulse peak catches up with the low-voltage amplitude, forming an output shock wave front with a very fast rise time. However, as the line is dispersive the output shortest rise time will be limited by the Bragg cutoff frequency

$$f_c = {}^{1}\!\Big/_{\pi\sqrt{LC(V_{max})}} \tag{1}$$

where C(Vmax) is the decreased capacitance at the maximum voltage applied. A rough estimate for pulse rise-time reduction is made by calculating the difference in time delay produced by the LC ladder sections between the lower amplitude portion and the peak of the propagating pulse as [1]

$$\Delta T = n(\sqrt{LC_0} - \sqrt{LC(V_{max})}) \tag{2}$$

where n is the section number of the line and C_0 the unbiased capacitance. A more accurate estimation is difficult because of the nonlinearity, but also due to the dispersion (phase velocity dependence on frequency). The final rise time of the output compressed pulse (shock wave front) is calculated such as $t_{ro} = t_{ri} - \Delta T$, where t_{ri} is the input pulse rise time with $t_{ri} > \Delta T$. However, the output rise time cannot decrease to zero, as the steepness of the output shock wave would become infinite if the input rise time is equal to the reduction factor ΔT. Then in the limit (when $t_{ri} \leq \Delta T$) the output shock wave rise time is limited ultimately by the lower cutoff frequency of the LC ladder as the pulse cannot be submitted to further sharpening. Consequently, the spectrum of frequencies from the shock wave exhibits higher-frequency components since the energy cannot propagate above f_c, producing at the output a series of narrow pulses (solitary waves) with a frequency of the order of $f_c/2$. Fig. 2 illustrates the burst of soliton oscillations produced at the output of an NLTL during the leading edge of the emerged pulse. Because of line losses, the ratio between the maximum and minimum voltage on the output modulation (VMD-voltage modulation depth) is attenuated.

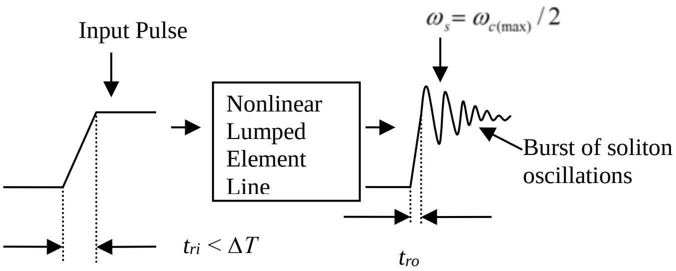

Fig. 2. Formation of a burst of short-duration solitons along the NLTL.

III. NLTL PROTOTYPES AND TESTS

In general, RF in the range of several tens of MHz is not difficult to produce by means of a low voltage n-section varactor diode line given in Fig. 3 with inductance in the μH range. As described elsewhere [8], RF generation of the order of 40 MHz with VMD between 5 and 10 V was obtained with a 30-section NLTL using BB809 varactor diodes and commercials inductors with L = 2.7 μH.

Thus, herein three NLTL prototypes with BB809 varactor diodes using different approaches were built to check line operation at higher frequencies (> 100 MHz) and higher voltages (> 30 V). The first approach for the BB809 diode line prototype based on Fig. 3 was built on a printed circuit board (PCB) with 30 sections to overpass RF frequency operation above 100 MHz using lower inductance in the nH. For this, air core inductors of 56 nH with high-frequency response (1.5 GHz) for use in PCBs were acquired. For the NLTL tests, a low voltage pulse generator (acquired from TTI Company) with output maximum amplitude of 12 V, pulse duration of 400 ns and 20 ns rise time was used. As the unbiased characteristic impedance of the line is 33 ohms and the generator output impedance of 50 ohms, in this case, pulse average amplitudes of about 4-5 V at NLTL input and output are obtained as shown in Fig. 4 by the pulse rise time transition, i.e. region of interest to illustrate the soliton burst formation. For lower values of L, the unbiased line impedance decreases, requiring pulse generators with extremely low impedances to obtain input pulse amplitudes near its maximum output voltage amplitude. Note also as the input rise time is of the order of the pulse rise reduction factor (20 ns) solitary wave oscillations are formed as a result of this condition discussed in section II. Despite NLTL is never matched because of the line nonlinear effect, the DC level does not vary much along the line when working with a load matched to the unbiased line. This produces input and output pulses in practice with nearly average amplitude plateaus as in Fig. 4, which eases the calculation of the oscillation frequency on each line section by estimating capacitance at given applied voltage V_{in} in agreement with Fig. 1. Anyway, as demonstrated by the frequency spectrum in Fig. 5 the oscillation frequency is near 150 MHz (measured on the curve knee) according to the half of the Bragg frequency with C= 22 pF at a reverse voltage of about 5.0 V (see Fig. 1).

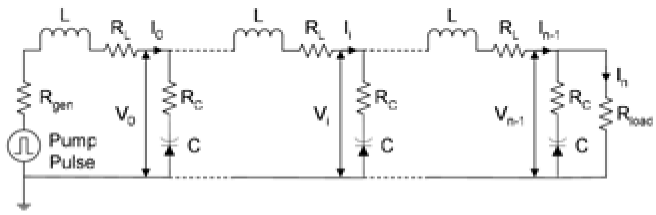

Fig. 3.A nth-section varactor diode line used to produce a burst of solitons.

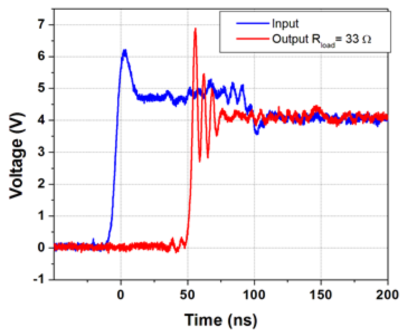

Fig. 4. Input and output pulses of the 30-section BB809/56 nH NLTL.

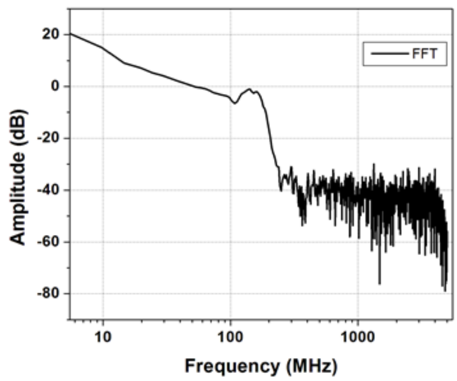

Fig. 5. Output FFT obtained with the BB809/56 nH NLTL.

Another approach made to operate at higher frequency was to increase the input pulse amplitude fed by the pulse generator so that the varactor diode could operate near its reverse breakdown (30 V) to reach the lowest capacitance of 5.0 pF as seen in Fig. 1. Because of the low output voltage and 50-ohms internal impedance of the pulse generator used, a homemade solution was implemented to test the NLTL at higher voltages. Fig. 6 shows the basic scheme of the HV low impedance pulse generator built with negative polarity because of the necessity of using a driver to feed higher current into the IGBT/MOSFET gate for a fast switching time (less than 100 ns). The 12V/20ns rise time low voltage generator controls the pulse duration. In this diagram, a resistance R2 of a few ohms is used to limit the initial current fed to the NLTL, where the discharge of a storage capacitor by means of solid-state switch closure produces a negative input pulse. As a result, due to this new configuration, the second prototype was rearranged by inverting the sense of the BB809 diodes in Fig. 3 to allow them to operate in the reverse mode with negative pulses. Fig. 7 shows this new NLTL arrangement for operation with negative pulses. For comparison of results with the first prototype, the section inductance was kept at 56 nH using the same air-core inductors.

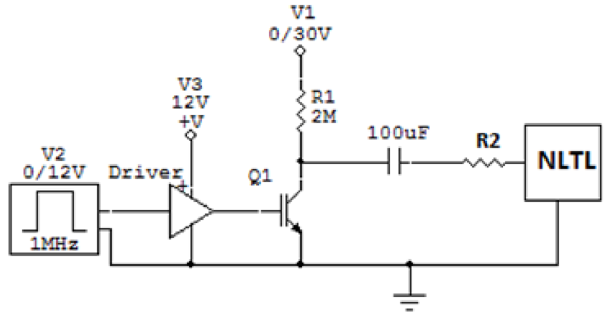

Fig. 6. Schematics showing the homemade pulse generator.

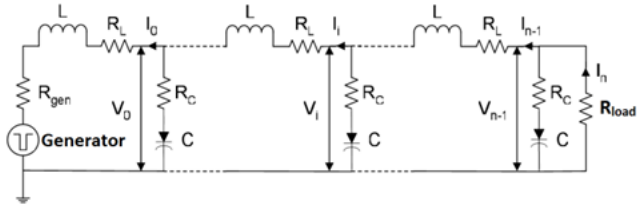

Fig. 7. Second NLTL prototype operating with negative input pulse.

Then, by charging the capacitor up to 30 V as in Fig. 6, Fig. 8 shows the negative pulse obtained with this second prototype on a load of 33 ohms matched to the unbiased line, where one can note that the obtained RF oscillation is around 300 MHz in both cases (see corresponding FFTs in Fig. 9). If this result is compared to that of Fig. 4, one can see that the VMD relative to the full amplitude is greatly reduced, which is explained by the presence of the stray inductance, whose effect is worse at HV operation by making the oscillations to fade away and reducing RF conversion efficiency. Therefore, it appears having a limit on L value that can be used on each section of an HV nonlinear LC line. Based on this result, this limit is set to 50 nH. As reported in [8], another increase in frequency by keeping L and C and the same input pulse voltage is made by increasing greatly the load above the unbiased line characteristic impedance. Fig. 9 shows this frequency increase up to almost 400 MHz for 500 ohms and 2.2 kΩ loads. However, the disadvantage of this method with unmatched load is that the oscillation frequency varies along the line because of the DC level variation caused by the line reflections.

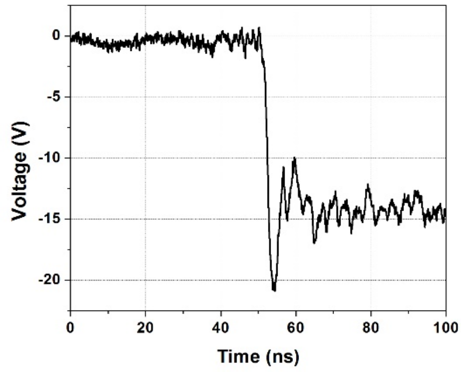

Fig. 8. Pulse on the load for the second NLTL prototype.

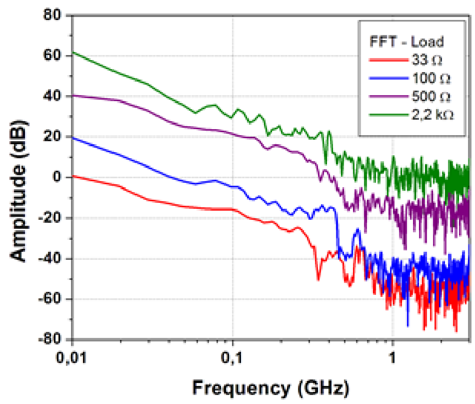

Fig. 9. FFT spectra show the oscillation frequency varying with the load.

Finally, a third NLTL prototype was built by stacking five diodes in series to check the minimum capacitance for high voltage operation of a nonlinear varactor lumped line. Again, the senses of the diodes on PCB board were rearranged to work in the reverse mode with pulses of negative polarity with L= 1.8 µH. This time, the pulser capacitor was charged up to 150 V to bias the diodes near their reverse breakdown voltage during pulse application. Fig. 10 shows the pulse obtained from the middle section, for instance, and Fig. 11 gives the corresponding FFT spectrum with a generated RF oscillation frequency of the order of 60 MHz. As the load is approximately matched to the unbiased line impedance, frequency oscillation practically does not vary along the line. Because of the 5-stage stack, the applied voltage across each diode remains near 30 V, keeping the diode capacitance at saturation, i.e. 5.0 pF according to Fig. 1. This means that an equivalent line section capacitance of C/n =1 pF was expected for the stack with a respective oscillation frequency of about 120 MHz according to half of the Bragg frequency. Of course, the experimental FFT in Fig. 11 with an oscillation frequency of about 60 MHz contradicts this result demonstrating that the stray capacitance has a greater effect on frequency decrease as it is probably higher than 1.0 pF.

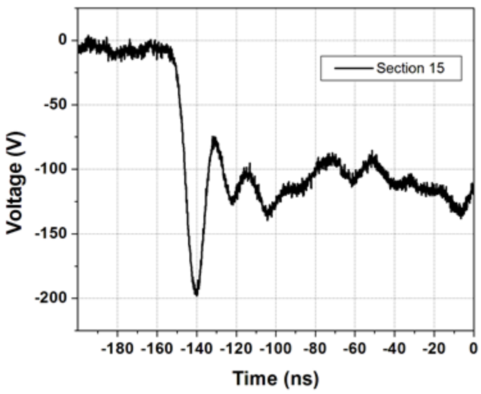

Fig.10. The output pulse on section 15 of the stacked diode prototype.

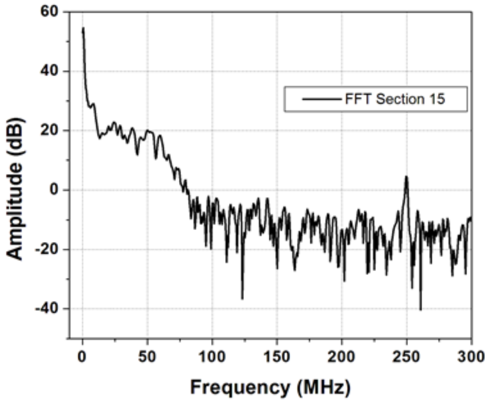

Fig.11. Corresponding FFT on section 15 of the stacked diode prototype.

IV. DISCUSSION

Scaling frequency up to 300 MHz by using low voltage (30 V) varactor lumped NLTLs has limitations because of the stray inductance that affects the VMD. Therefore, inductances of the order of 50 nH seem to be the minimum acceptable values, otherwise, parasitic inductances in the PCB would decrease VMD, fading away the oscillations or decreasing significantly the frequency if they are higher than the section inductance. On the other hand, stacking diodes in a varactor NLTL for HV operation near to the diode breakdown voltage has also constraints as stray capacitance resonates with L producing decreased frequencies below the calculated oscillation frequency according to $f_c/2$ if stacked capacitance is probably below 10 pF. In view of that, the maximum oscillation frequency to be obtained with a PCB lumped varactor NLTL should be around 220 MHz, considering practical values obtained herein of about 50 nH and saturated 10 pF per line section. Therefore, in practice, a better approach to extend the lumped LC NLTL in excess of 200 MHz for HV operation would be the use of SiC Schottky diodes as they have high reverse breakdown voltage (1 kV) and strong nonlinear C behavior in pF range. For instance, Fig. 12 shows the capacitance versus reverse voltage of the C4D05120E Schottky diode obtained from its datasheet, which shows a saturated capacitance of less than 20 pF at 1 kV.

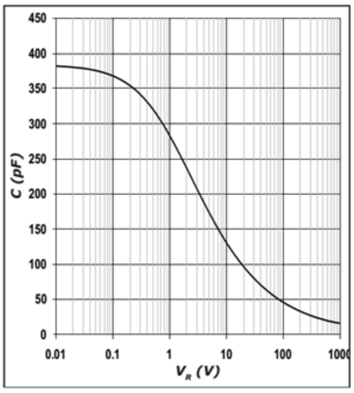

Fig.12. C×V curve of the C4D05120E diode datasheet, CREE vendor.

V. CONCLUSION

In this paper, it was demonstrated that NLTLs could be used for pulse sharpening or RF generation depending on the rise time of the input pulse applied. Under RF generation, it was noted that there is a limit for decreasing the line component (L or C) in order to obtain a high operation frequency above 200/300 MHz. However, as discussed herein there are good prospects for operating varactor NLTLs in an HV environment using SiC Schottky diodes of 1.0 kV breakdown voltage. In a near future, these diodes could replace ceramic capacitors in HV NLTLs for applications in transmitting systems of pulsed radars operating at L-band, for example.

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