STUDIES OF NONLINEAR MEDIA WITH ACCELERATOR APPLICATIONS*

P. Schoessow#, A. Kanareykin, Euclid Techlabs LLC, Solon, OH 44139, USA
S.Baturin, St.Petersburg Electrotechnical University "LETI", St.Petersburg, Russia
V. P. Yakovlev, Omega-P, Inc., New Haven, CT, USA

Abstract

Materials possessing variations in the permittivity as a function of the electric field exhibit a variety of phenomena for electromagnetic wave propagation such as frequency multiplication, wave steepening and shock formation, solitary waves, and mode mixing. New low loss nonlinear microwave ferroelectric materials present interesting and potentially useful applications for both advanced and conventional particle accelerators. Accelerating structures (either wakefield-based or driven by an external rf source) loaded with a nonlinear dielectric may exhibit significant field enhancements. In this paper we will explore the large signal permittivity of these new materials and applications of nonlinear dielectric devices to high gradient acceleration, rf sources, and beam manipulation. We describe planned measurements using a planar nonlinear transmission line to characterize in detail the electric field dependence of the permittivity of these materials. We will present a concept for a nonlinear transmission line that can be used to generate short, high intensity rf pulses to drive fast rf kickers.

INTRODUCTION

Technologies based on nonlinear optical phenomena have had a significant impact in the laser field, where harmonic generation and other effects are routinely and productively used. Similar effects have been employed at rf frequencies where the nonlinear properties of ferrite loaded transmission lines have been used to produce short rf pulses at MHz frequencies [1]. Substantial progress in the area of microwave dielectrics, particularly ferroelectric-based ceramic materials that have been developed by Euclid Techlabs, offers the possibility of extending the frequency range of nonlinear rf devices to X-band and above.

Serious interest and progress in microwave dielectric materials has arisen in part from studies of dielectric loaded accelerating structures and beam driven microwave sources [2]. Also, early on in the development of quantum electronics nonlinear dielectrics were already being considered as harmonic generating devices [3]. The properties of wakefields in a nonlinear dielectric waveguide were initially studied a number of years ago [4]. Numerical results showed that some wave steepening did occur and could act to enhance the wakefield acceleration gradient. Further development of these results into a working technology was hampered by the unavailability of suitable low loss, low permittivity dielectrics with fast response times and suitably high beam currents for wakefield experiments. A reexamination of the potential applications of nonlinear dielectric waveguides has been prompted by substantial progress in the area of microwave dielectrics, particularly ferroelectric-based ceramic materials.

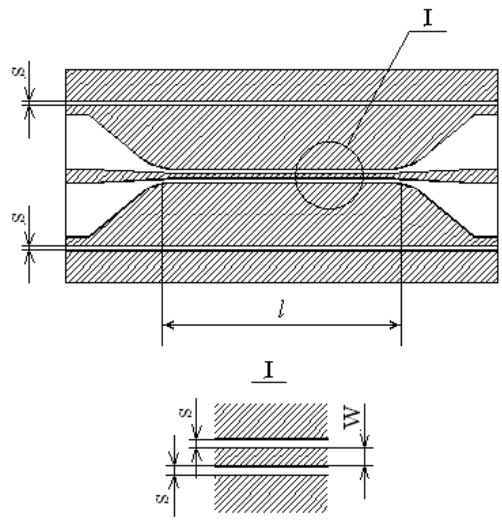

Figure 1: Schematic of a coplanar nonlinear transmission line [6] similar to what is planned for the nonlinear dielectric measurements. Crosshatched areas; copper; open areas: ferroelectric. Dimensions s = 20 µm, W = 40 µm, l = 6 mm.

A ferroelectric ceramic possesses an electric-field-dependent dielectric permittivity that can be rapidly varied by an applied bias voltage pulse. Ferroelectrics have unique intrinsic properties that make them extremely interesting for a number of high-energy accelerator and microwave applications. Response times of ~10-11 sec for the crystalline form and ~10-10 sec for ceramic compounds have been measured. Unlike semiconductors and plasma devices, ferroelectrics allow control of their dielectric properties in two directions using a single external control pulse, offering unique capabilities for high-power switching and tuning devices intended for accelerator and other rf applications [5, 6].

The high dielectric constant of ferroelectrics (~500) is not desirable for many applications. For example, the use of high permittivity materials leads to enhanced wall losses in cylindrical geometries. Lowering the permittivity (and the loss tangent) through the use of ferroelectric-low loss tangent dielectric composites is the approach we plan to follow. Recent theoretical work [7] has shown that ferroelectric composites can be designed that also preserve or even enhance the tunability of the material, and DC permittivities ~100 in nonlinear ferroelectric ceramics are feasible.

In the tunable devices studied so far by Euclid, the electric field of the rf signal is much smaller than the strength of the dc bias field used of to modify the average permittivity of the loading material. In these cases the rf field has a negligible additional effect on the permittivity. We consider in this proposal the large signal case where the permittivity of the ferroelectric loading of a dielectric wakefield structure or resonator is significantly affected by the strength of the rf field.

NONLINEAR TRANSMISSION LINE

Paraelectric film-based planar transmission lines (slot lines, coplanar waveguides) are broadband fast-acting tunable lines with relatively low losses (for BST composite films tan $\delta < 10^{-2}$, f = 1–10GHz) and suitable tunability (variation of the dielectric constant with applied field) [6]. Therefore they can be considered as candidates for use in UWB (ultrawideband) techniques (for pulse compression in particular). A transmission line bench test unit is being used for diagnosing the nonlinear properties of candidate ferroelectric-ceramic composites. Fig. 1 shows an example of a transmission line used for characterization of ferroelectric films [6]. The high voltage test pulse is applied to the central conductor. The outer slits serve as dc breaks so that a bias voltage can be applied between the central conductor and the ground pads if desired.

Analysis of transformation of the shape (including the formation of a shock wave) of a transient rf pulse propagating along the line makes it possible to obtain the time and frequency domain measurements of the generated harmonics over a broad frequency range for E-fields of varying magnitudes. A factor of 10 compression (from 130ns to 13ns) of the leading front of a pulse has been demonstrated in ref. [8] for a ceramic ferroelectric for a pulse with a peak electric field E~1V/μm. The nonlinear properties of ferroelectric ceramics with advanced composition and construction with a pulser voltage of 5-10kV with nanosecond pulse time duration are currently being studied.

SOLITONS IN NONLINEAR DISPERSIVE DEVICES

We have been developing a FDTD code to study soliton formation and propagation that we plan to use for the design of the nonlinear transmission line in this project. Fig 2a shows a time integration of the KdV equation, a simulation of a soliton propagating in a uniform structure. In this case the analytic solution of the form $\psi(z,t) = A\,\mathrm{sech}^2(B(z-ct))$ was used as the initial waveform. Using a variant of the algorithm (1.4) applied to (1.5), and using periodic boundary conditions, we obtain the results in Fig. 2a. As expected, the wave propagates without changing form.

It would seem that this effect would be less useful in transmission line based short pulse sources than simple shock wave formation, since it would appear that once a soliton is formed, it does not change its shape or its amplitude as it propagates. The work of Ikezi [10] contains a number of novel ideas relevant to nonlinear transmission lines. Most important for our purposes are that the dispersion of the line can be controlled by incorporating an almost periodic modulation of the permittivity along the direction of propagation, and that the stability of solitons implies that by gradually modifying the dispersion and nonlinearity the amplitude of the soliton pulse can be enhanced in a controlled manner while being compressed axially. Fig. 2b shows a soliton evolving from the same initial conditions as Fig 2a, but with the dispersion of the line decreasing linearly with distance. In this case the soliton maintains its basic form while increasing in amplitude and decreasing in duration. This effect can be used to provide a non-oscillatory and symmetric pulse compared to a simple nonlinear line.

We note that both the spatial variation of the permittivity and the nonlinearity of the ferroelectric can be adjusted electrically through the appropriate placement of dc bias electrodes. Even with a large rf electric field present, some permittivity control is obtained by application of a dc bias normal to the rf electric field [11, 12].

ENGINEERED DISPERSION IN NONLINEAR DIELECTRIC DEVICES

We have used our in house Slab code to examine the properties of a dispersive transmission line. For this test case the dielectric itself was assumed to be linear and nondispersive. A thin thickness b of dielectric is sandwiched between two conducting plates. The permittivity is assumed to vary along the propagation direction as $\varepsilon(z) = \varepsilon_1 + \varepsilon_2 \sin(2\pi k_1)$

where ε_1=average permittivity, and ε_2=permittivity contrast. $k_1 = 2\pi/d$, where d is the period of the spatial modulation. For definiteness we take ε_1=100, ε_2=20, d=2 mm, and b=1 mm. Furthermore, we consider the case of a TEM wave, i.e. the only field components present are E_x and H_y. The drive signal is assumed to be a time harmonic E_x applied at z=0 and not varying with x. The periodicity leads to the formation of a band gap at $k_0=\pi/d$, which in this case corresponds to approximately 7.5 GHz. In the neighborhood of k_0, the dispersion curve is distorted, which Ikezi showed provides the required third derivative dispersion term needed for soliton formation. Fig. 3 shows the Brillouin diagram computed using our code. For wave numbers outside the band gap the points lie on the line $\omega = ck/\sqrt{\varepsilon_1}$, the analytic result for the dispersion relation when ε_2=0.

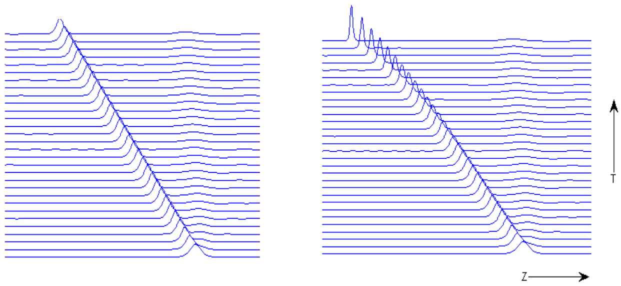

Figure 2: (a) Numerical calculation of the evolution of a KDV soliton. Periodic boundary conditions are applied. The structure is uniform in the direction of propagation and the soliton propagates unchanged in shape. (b) Propagation in a structure with linearly decreasing dispersion β(z). The pulse now increases in amplitude as it sees a gradually smaller values of β.

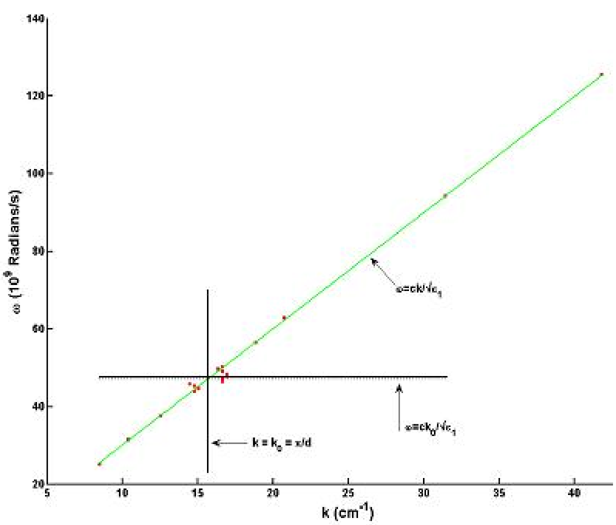

Figure 3: Brillouin diagram for the structure showing a band gap at $k_0=\pi/d$, where d is the axial period of the permittivity. Points correspond to numerical results.

NEXT STEPS

Using the results of the transmission line measurements, we plan to design and simulate a nonlinear wakefield structure. We plan to upgrade the Arrakis code [13] to be able to handle the large permittivities involved in these calculations. This will primarily involve the use of higher order approximations at structure boundaries where current instability problems originate. Based on extrapolating the linear theory we expect that observation of nonlinear effects will require a high charge bunch train.

Fortunately these bunch trains are available at the Argonne Wakefield Accelerator. Experiments at the AWA are planned for Phase II to study dynamic nonlinearities of high frequency ferroelectrics in dielectric wakefield accelerators. Initial experiments would consist of instrumenting the structure with field probes and measuring the waveforms as a function of beam intensity and bunch length. The heterodyne wakefield rf measurement system at the AWA [14] is capable of diagnosing very high frequency waveforms like those present in this experiment.

The AWA facility is also implementing a witness beam system for direct wakefield measurements. We plan to perform a beam acceleration experiment using a nonlinear dielectric structure when this new capability becomes available.

REFERENCES

[1] I. Kataev, *Electromagnetic Shock Waves*, Iliffe 1966

[2] e.g. see M. Conde *et al.*, 2006 *Advanced Accelerator Concepts,,* M. Conde, C. Eyberger eds. p.260.

[3] M. DiDomenico, D.A. Johnson, R.H. Pantell, "Ferroelectric Harmonic generator and the Large-Signal Microwave Characteristics of a Ferroelectric Ceramic", *J. Appl. Phys* 31(5) 1962 pp. 1697-1706

[4] P. Schoessow, *Proc. 1989 Workshop on Advanced Accelerator Concepts,* p. 371

[5] V.P. Yakovlev, O.A. Nezhevenko and J.L. Hirshfield. PAC2003, Portland, p. 1150, 2003,

[6] V.P. Yakovlev, O.A. Nezhevenko, J.L. Hirshfield, and A.D. Kanareykin. AIP Conference Proceedings, Vol. 691(1), pp.187-196, 2003.

[7] V. Sherman *et al.*, *J. Appl. Phys.* **99**, 074104 (2006); A. Tagantsev *et al.*, "Ferroelectric Materials for Microwave Tunable Applications", *Journal of Electroceramics*, 11, 5–66, 2003

[8] A.Kozyrev, *et al."* Nonlinear Behavior of Thin Film $SrTiO_3$ Capacitors at Microwave Frequencies", *J.Appl.Phys.* 1998 V.86, N6, p.3326

[9] N. Zabusky, M. Kruskal, Phys. Rev. Lett. 15, 240 (1965)

[10] H. Ikezi, "Compression of a single electromagnetic pulse in a spatially modulated nonlinear dielectric", J. Appl. Phys. 64 3273 (1988)

[11] A. Kanareykin *et al.*, "Experimental Investigation of an X-Band Tunable Dielectric Accelerating Structure", *Proc. PAC 2005,* TPAE061

[12] A. Kanareykin *et al.*, "Ferroelectric Based Technologies for Accelerator Component Applications", Proc. PAC 2007

[13] P. Schoessow, Wei Gai, *Proc. 15th Advanced ICFA Beam Dynamics Workshop 1998,* P. Chen ed. p. 289

[14] A. Kanareykin *et al.*, "Beam Breakup Instabilities in Dielectric Structures"**,** PAC07 Proceedings, FRPMS094