EFFECTS OF DIELECTRIC WIDTH EXTENSION IN A PARALLEL-PLATE BLUMLEIN LINE

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KEY TERMS

Blumlein line, pulse generation, transient response, parallel-plate line

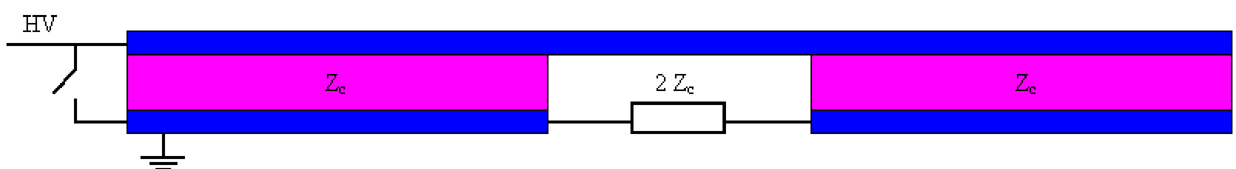
ABSTRACT

Computational analyses are performed on a parallel-plate Blumlein line with a nonstandard width of a dielectric as a way to mitigate against the dielectric breakdown. We report its effects on the electric field, propagation time of the transient effect, characteristic impedance of the line, and the output pulse.

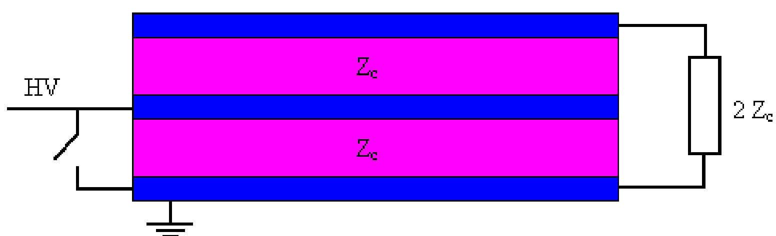
I. INTRODUCTION

High-power microwave (HPM) technology has been in use for various applications [1]-[3], but it was characterized by large-scale dimensions of the devices. Recent technological advances have directed further research towards reduction of dimensions of HPM components to a portable scale. The key areas to give a breakthrough are identified as: materials, optimization (by making use of electromagnetic modeling), and thermal management [4]. As for materials, the aim is to achieve dielectric materials with high permittivity values and high breakdown strength. For that purpose, there is an increased interest in novel ceramic materials being under investigation [5] while the studies on liquid and gaseous dielectrics are continuing [6]. Likewise, there is a concurrent continuing investigation on switches [7]. Anticipated use of advanced materials will enable desired reduction of dimensions, but to achieve a proper performance of the system, an optimization between the electrical and geometrical parameters is needed.

A component of an HPM system responsible for generation of a high power is a pulse forming line (PFL). We had chosen a parallel-plate Blumlein line (PPBL) configuration [8]-[10]. A basic form of a PPBL is shown in Fig. 1(a). However, this basic configuration of the line is not compact enough to support our goals. A more compact version of it is shown in Fig. 1(b). We refer to it as a *stacked*- or a *compact- Blumlein line* (BL). To compact it even more, the straight BL (SBL) from Fig. 1(b) can be folded (FBL).



(a)



(b)

Fig. 1 Blumlein line configurations: (a) basic; (b) stacked or compact

Whether it will be an SBL from Fig. 1(b) or an FBL, such a PFL is to be typically charged with hundreds of kilovolts and should deliver the output power of the order of gigawats. To realize that, the pulse has to be of the order of tens of nanoseconds (preferably longer than 50 ns). To satisfy that goal, one can either use a longer line, as the pulse duration directly depends on the length of the line, or use a dielectric with a higher permittivity value.

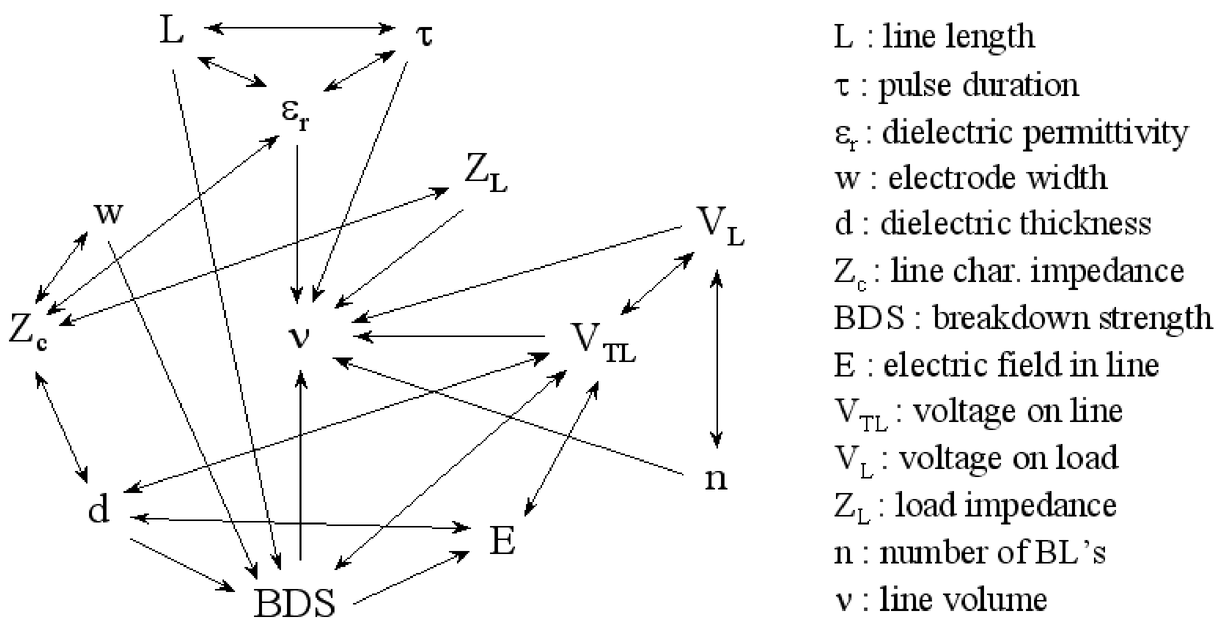


Fig. 2 Relationships betweens the parameters in a Blumlein Line

To adequately design a BL, there is a number of parameters that must be mutually matched, as illustrated in Fig. 2. Changing the value of one of them instantaneously pulls the values of a few others, which may lead to implausible values for some of them. For example, the pulse duration is expressed as

$$\tau = \frac{2 \cdot L \cdot \sqrt{\varepsilon_r}}{c} \tag{1}$$

where c is the velocity of light. The characteristic impedance of the line, for a sufficiently large ratio of w/d [11], is defined by

$$Z_c \approx \frac{377 \cdot d}{\sqrt{\varepsilon_r} \cdot w} \tag{2}$$

If we increase the permittivity value ε_r, that will produce a longer pulse. At the same time, it will decrease Z_c. But, for a given load impedance Z_L, the line impedance Z_c is a strictly prescribed value and it may not change. Thus, to keep the line impedance unchanged, we have to change either *w* or *d*. A change in *d* will either affect the magnitude of the electric field, or will require some adjustment in the applied voltage (which then affects the voltage on the load). At the same time, a change in *w*, as well as a change in *d*, will differently relate to the dielectric breakdown strength (*BDS)*. As a consequence, an actual *BDS* may become insufficient for the desired *E* (or V_L).

One of the studies undertaken to explore the possible mitigation of the breakdown is on the effects of a nonstandard design of the dielectric. By "nonstandard" we refer to a dielectric which is wider than the width of the conductor plates. This design had been used in a somewhat different experimental setting by researchers at Sandia National Laboratories [12]. The idea is that a wider dielectric will enable a more gradual decay of the electric field around the edges of the plates (where high concentration of the electric field develops) and thus help mitigate against a premature breakdown in the dielectric.

With respect to dimensions reduction, it is relevant to test what benefits and penalties such a wider dielectric may have on the pulse forming process. For that purpose, we define a new variable, named *DEW* (dielectric extra width). *DEW* is expressed as a percentage for which the dielectric is wider than the plates. All the electromagnetic modeling and computations was accomplished using CST Microwave Studio™ software on a PC with a single Pentium 4 processor at 3GHz, and 1GB RAM.

II. ANALYSES

A. DEW Effect on the Propagation Time

To measure effect of DEW on the propagation time in an SBL (excited by a switch), we install probes along the line length, as shown in Fig. 3. The measured time difference between the peaks of the pulse on different probes is denoted as Δt_m. The distance between the probes is Δx. We then compare the measured time Δt_m, and the theoretically predicted time Δt, known as

$$\Delta t = \frac{\Delta x}{c} \cdot \sqrt{\varepsilon_r} \tag{3}$$

The following behavior is observed: *as DEW increases, there is a small, hardly noticeable, increase in the propagation time*, in general. (This slight increase will be mentioned more specifically later in the discussion on the pulse form.) Second, *the propagation times in the bulk of the line are longer than those near the edges*.

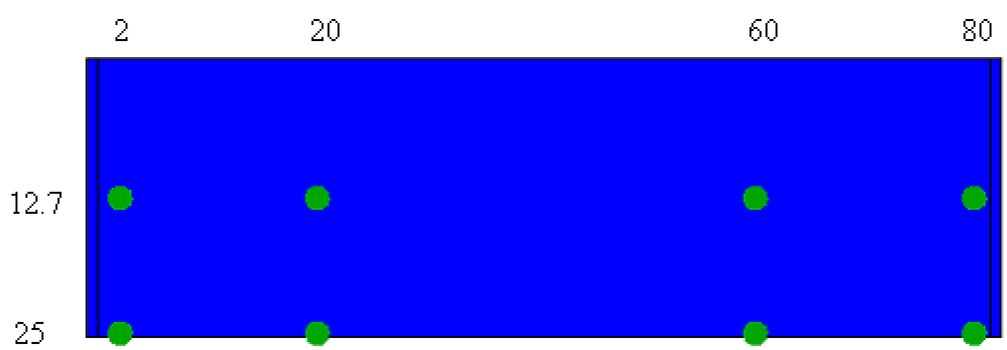
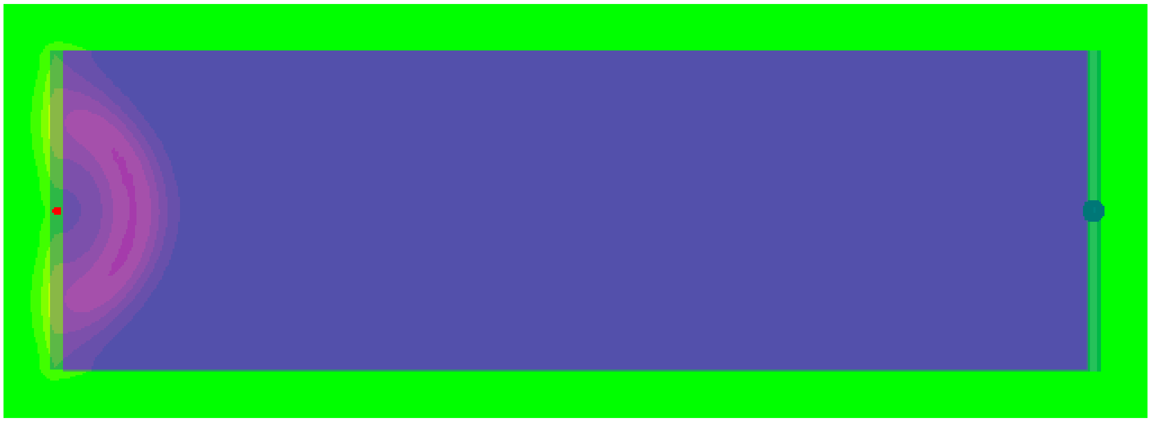
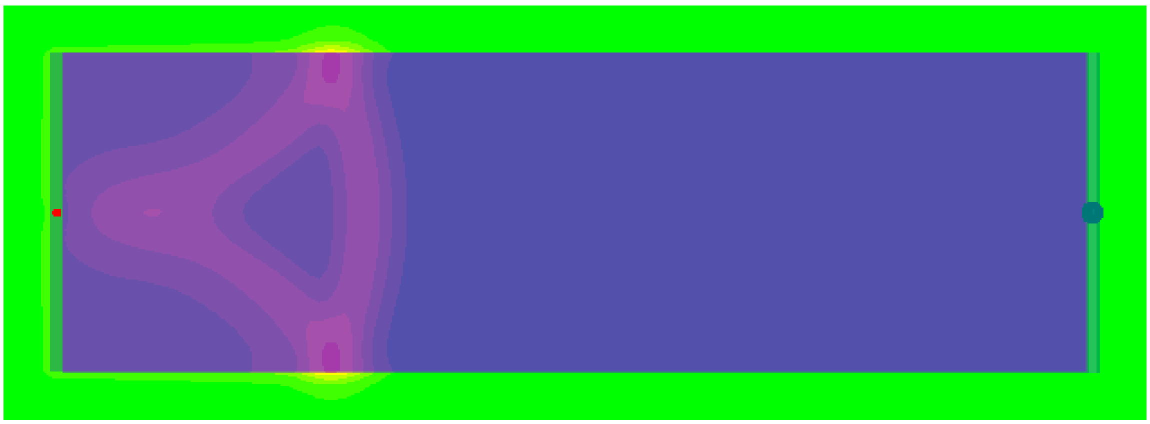


Fig 3   Top view on the arrays of probes installed in the line



(a)



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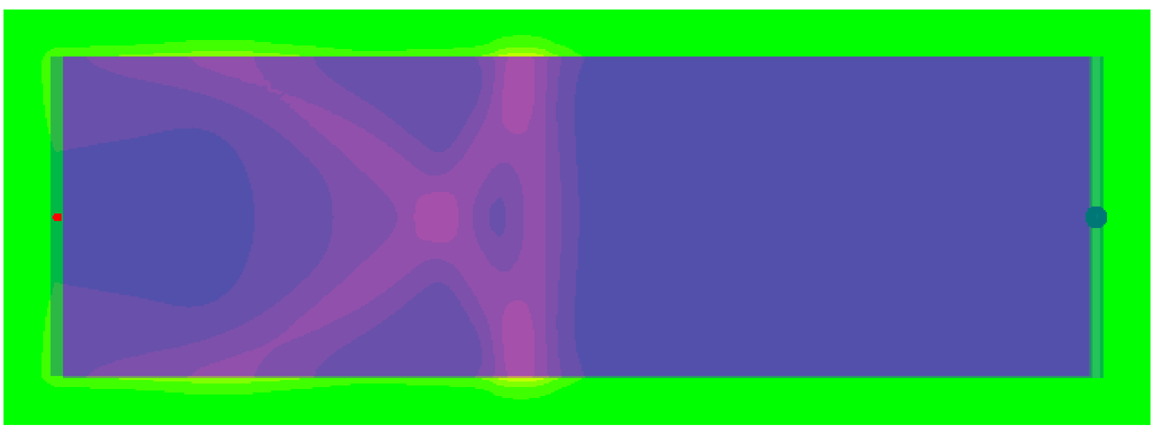

(c)

Fig. 4 Wave propagation in a PPBL, originated in a point source (switch): (a) spherical wave near the source; (b) wave converting from a spherical into a planar form; (c) a plane-front wave with its tail bouncing off the edges

One could interpret this by the vicinity of air near the edges, which makes the effective value of the permittivity somewhat lower than the nominal value, and thus makes the propagation time shorter. However, when we repeated the experiment using a waveguide type (plane-wave) of the excitation, the results for the edge and the bulk overlapped and showed an agreement with the theoretically computed values of Δt. That means that the theoretical values given by (3) are related to a plane-wave excitation of the line. The original discrepancy of the curves is primarily due to a point-source excitation. With such an excitation, the wave first starts propagating as a spherical wave and yet later straightens up into a (nearly) plane wave. Figure 4 illustrates three characteristic time instants of this point-source-originated propagation.

Besides the difference in the wave velocity between the bulk and the edge, it also turns out that the velocity of the wave varies from segment to segment down the line (i.e. it is different on the segment x=[2,20], from the velocity on the segment x=[20,60] or x=[2,80]).

B. DEW Effect on the Electric Field

For a BL with w = 25.4 cm, and ε_r = 3.5, the probes are initially installed across an arbitrarily selected cross-section (x = 10 cm) of the dielectric slab. They will enable recording of the electric field variations in both time and space. Due to the axial symmetry of the field, the probes are set only in one half of the line, as illustrated in Fig. 5 for DEW=10%. We plot dependency of the electric field ('E-field', for brevity) for the applied input voltage of 1 V (for generality purpose). All the readings are referred to the same time instant for which the field is maximal on the mid probe (z = 12.7 cm).

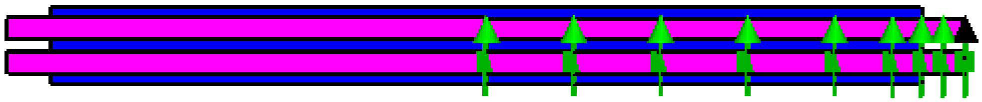

Fig. 5   Probes installed over a cross-section of SBL for DEW = 10%

Figure 6 plots the magnitude of the E-field against the positions of the probes, having DEW as a parameter for each curve. It indicates that for DEW = 0%, the field gets lower at the edge (z = 25.4 cm), whereas for DEW > 0%, the field is higher and this observed increase in the E-field value is undesired. Outside the plates (z > 25.4 cm), the field first has a rapid drop, as expected, but it then decays more gradually. It thus shows how use of dielectric extension enables a more gradual decay of the field in the vicinity of the edges in order to circumvent for the breakdown. At each point in this region, first additional extension of the dielectric width further lowers the field magnitude, but the subsequent extensions make no change (the curves are overlapped). This can be best observed for the first two extensions (z = 26.035 cm, and z = 26.67 cm).

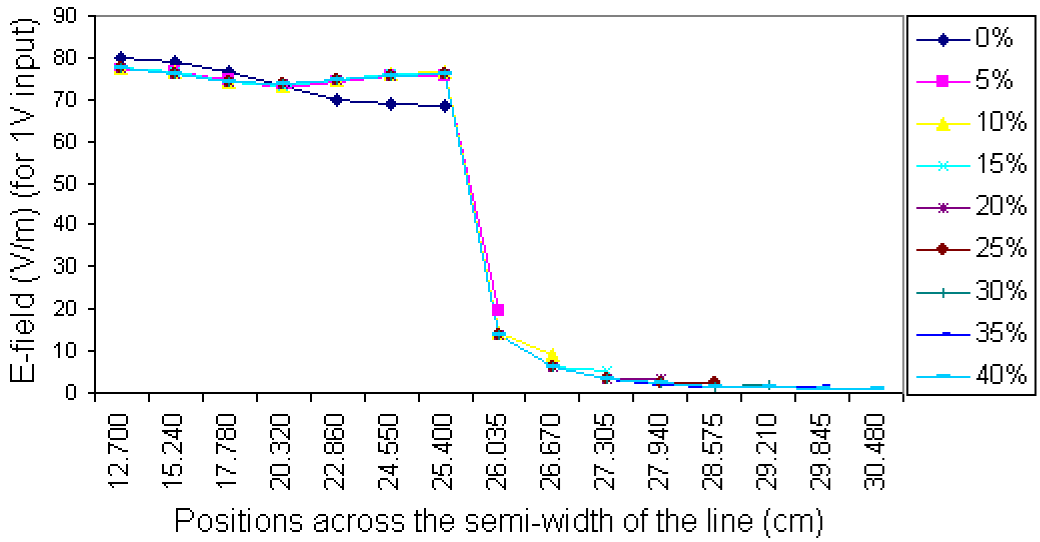

Fig. 6   Variations of E-field across semi-width of SBL, with DEW as a parameter

As several curves in Fig. 6 are practically overlapped for different values of DEW, it is easier to see the difference if we plot the results differently. Figure 7 thus plots the E-field from Fig. 6 against the DEW, with the position of the probe as a parameter. It is now easy to notice that the magnitude of the E-field practically does not change for DEW > 5%, or, at most, DEW > 10%. However, though indicative, this was essentially just a special case since we set the probes across an arbitrary cross-section. Due to the subtle motion of the wave, the situation may be different across some other cross-section, not only quantitatively, but possibly also qualitatively. What matters for the breakdown in the line is the maximum value of the E-field, whenever and wherever it occurs during the pulse-forming process.

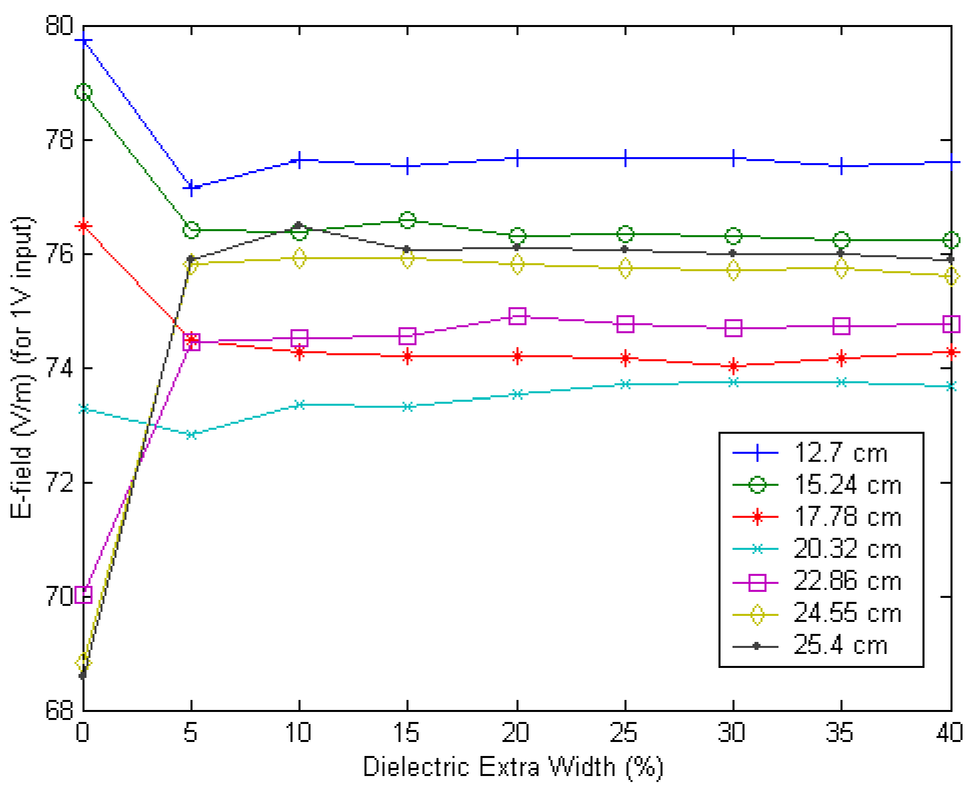

Fig. 7 Variations of the E-field on the probes inside the plates

Because of that, we further observed the maximum value of the field on that "whenever, wherever" principle. As the minimization of the dimensions is sought, and to test for more cases, the computation was further done for w = 12.7 cm, w = 9 cm, and w = 6.35 cm. The results indicate that no general trend of values can be claimed. From all these cases, the lowest value of E_{max} turns out to be for DEW = 0%, or, eventually, for DEW = 5%. The analyses suggest that the result of E_{max} and the variation of E_{max} with respect to DEW depend on the particular width of the plates. Since the wave starts propagating from a point-source, the distance between the source and the edge of the plate forms the field pattern specific to a particular width of the plate.

C. Characteristic Impedance of the Line

The effect of DEW on the characteristic impedance of the line was tested for three values of dielectric permittivities (3.5, 14, and 57) and two widths of the electrodes (25.4 cm, and 12.7 cm). As Z_c appeared to change most abruptly for small values of DEW, additional values of DEW = 2%, and 4% were inserted. Table I shows the results obtained, while Fig. 8 shows it graphically for the second, and the third column of Table I. *Clearly, for equal-initial-impedance lines, the impedance of a wider line has lesser offset from the nominal value (DEW = 0%).* Normalizing the values in Table I to the value for DEW=0% and comparing the first two columns, for example, it can be seen that the coefficients as a function of DEW are not independent of w even for the same ε_r (which is different from the behavior of the standard parallel-plate line impedance). Secondly, the coefficients as a function of DEW are not invariant for different values of ε_r even for the same ratio w/d (e.g. compare the first, third, and the fifth column).

TABLE I
CHARACTERISTIC LINE IMPEDANCE OF SBL

	SBL					
	ε_r = 3.5		ε_r = 14		ε_r = 57	
	w = 12.7	w = 25.4	w = 12.7	w = 25.4	w = 12.7	w = 25.4
DEW, %	Zc [ohm]	Zc [ohm]	Zc [ohm]	Zc [ohm]	Zc [ohm]	Zc [ohm]
0	10.0903	5.0411	5.0491	2.5203	2.5004	1.2492
2	9.9144	4.9645	4.9616	2.4837	2.4562	1.2314
4	9.7724	4.9325	4.8926	2.4700	2.4257	1.2247
5	9.7540	4.9243	4.8803	2.4657	2.4224	1.2231
10	9.6435	4.9081	4.8349	2.4596	2.3972	1.2200
15	9.5997	4.9054	4.8176	2.4583	2.3913	1.2194
20	9.5820	4.9048	4.8087	2.4578	2.3880	1.2192
25	9.5743	4.9050	4.8063	2.4578	2.3843	1.2191
30	9.5710	4.8954	4.8035	2.4526	2.3834	1.2169
35	9.5696	4.8953	4.7990	2.4526	2.3858	1.2168
40	9.5690	4.8952	4.8018	2.4526	2.3849	1.2168

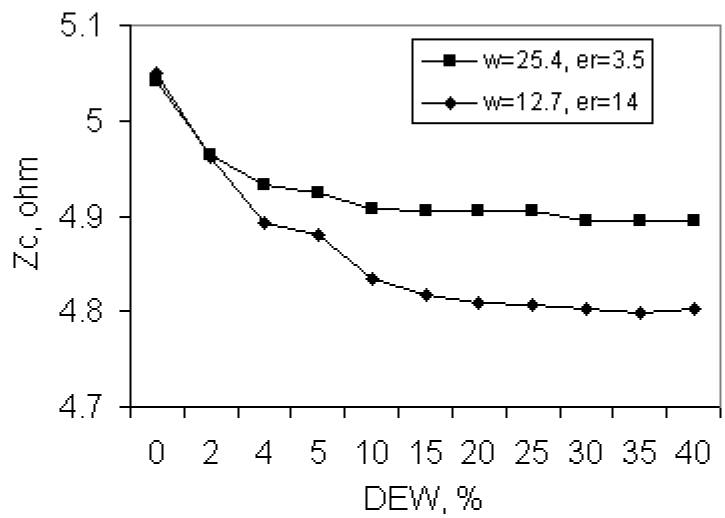

Fig. 8 Comparison of Z_c of two designs

TABLE II
RELATIVE ERROR OF Z_c(DEW) vs. NOMINAL Z_c

	SBL					
	ε_r = 3.5		ε_r = 14		ε_r = 57	
	w = 12.7	w = 25.4	w = 12.7	w = 25.4	w = 12.7	w = 25.4
DEW, %	Zc [ohm]	Zc [ohm]	Zc [ohm]	Zc [ohm]	Zc [ohm]	Zc [ohm]
0						
2	-1.74%	-1.52%	-1.73%	-1.45%	-1.77%	-1.43%
4	-3.15%	-2.15%	-3.10%	-2.00%	-2.99%	-1.97%
5	-3.33%	-2.32%	-3.34%	-2.17%	-3.12%	-2.09%
10	-4.43%	-2.64%	-4.24%	-2.41%	-4.13%	-2.34%
15	-4.86%	-2.69%	-4.58%	-2.46%	-4.36%	-2.39%
20	-5.04%	-2.70%	-4.76%	-2.48%	-4.50%	-2.41%
25	-5.11%	-2.70%	-4.81%	-2.48%	-4.64%	-2.41%
30	-5.15%	-2.89%	-4.86%	-2.69%	-4.68%	-2.59%
35	-5.16%	-2.89%	-4.95%	-2.69%	-4.58%	-2.60%
40	-5.17%	-2.89%	-4.90%	-2.69%	-4.62%	-2.60%

Now we can estimate the upper error bound. Table II contains relative errors of Z_c(DEW>0%) with respect to Z_c(DEW=0%). The following is observed: *for some ε_r, relative error is smaller for wider plates; for some w, relative error is smaller as ε_r increases.* The latter is especially interesting as the use of dielectrics with higher permittivity values is anticipated. If, using the discussion made in the section on the E-field, we limit the dielectric width to DEW ≤ 10%, then the relative error will remain under or about 5% from the nominal value (lines narrower than 12.7 cm were not analyzed here, but higher ε_r and smaller w compensate each other's effect on Z_c).

D. Effect of DEW on the Output Pulse

It turns out that DEW has a negligible effect on the pulse width comparing to these other factors. First, the *line width* affects the pulse shape and the duration by means of the responsiveness of the line, as it is shown in Fig. 9 for four equal-impedance lines with different widths of their electrodes. Narrower lines have a faster response, which converges to an ideal 'gate' shape (red line, w = 6.35 cm), whereas wider lines exhibit a charging/discharging-like characteristics of a capacitor (purple line, w = 25.4 cm).

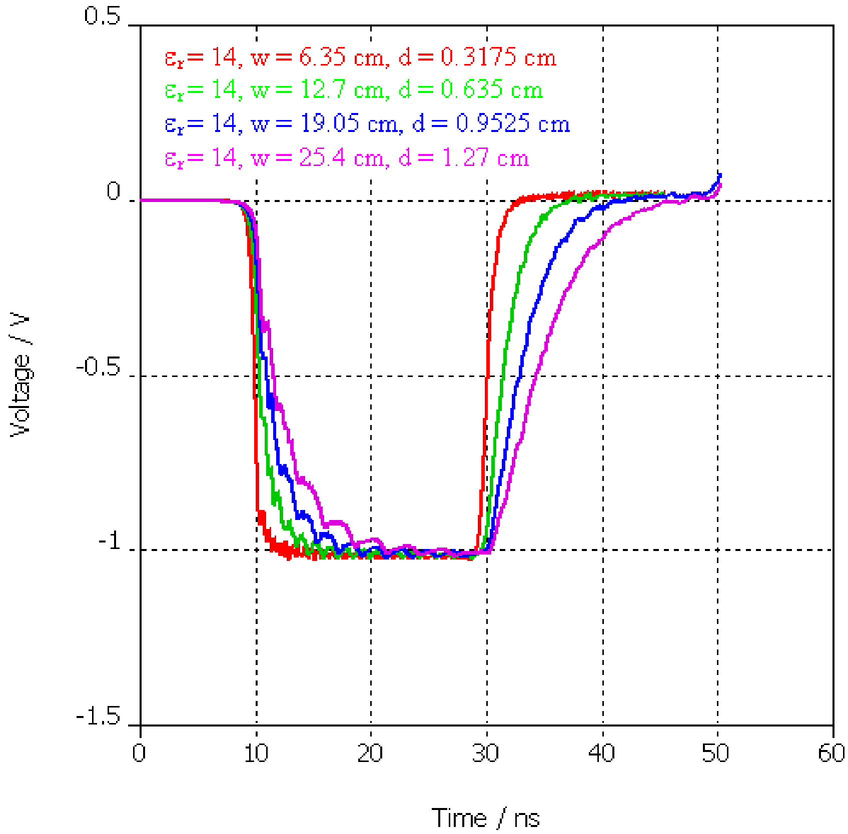

Fig. 9 SBL response to four line widths

This is also another source of the discrepancy between the theoretically calculated width of the pulse, using (3) with $\Delta x = 2 \cdot L$, and the real duration of the pulse (measured at the half of its magnitude).

Besides that, the absolute value of the discrepancy between the theoretical prediction and an actual duration of the pulse increases with an *increase in the value of* ε_r, but the relative error of that discrepancy actually decreases. The line of w = 25.4 cm has this discrepancy above 10%, whereas the line with w = 12.7 cm scores below 4%. Finally, the additional effect that DEW has on the pulse width is that the pulse is prolonged merely about 0.2 ns. Similarly to the situation with the electric field change with respect to DEW, the pulse extension is here most "significant" for DEW = 5%, whereas the curves for DEW ≥ 10% are practically bundled tightly to each other.

III. CONCLUSIONS

Effects of a use of a nonstandard design of the dielectric in a PPBL on the wave propagation time, electric field, characteristic impedance, and the pulse shape were concisely reported. In addition, we also briefly discussed how changes of parameter values (such as ε_r, and w) affect competitiveness of a particular line design.

In case of the propagation time and the pulse width, though not critical for a practical design, the analyses explained some discrepancies between the theoretical predictions and the real results. In case of the magnitude of the electric field and its relation to the breakdown, the analyses indicate that use of dielectric width extension may be beneficial for breakdown mitigation, but that a particular line width must be analyzed before employing it. If used, DEW wider than 10% does not seem to be advantageous for anything, whereas, on the other hand, it degrades the compactness of the line.

REFERENCES

1. J. Benford and J. Swegle, *High-Power Microwaves*, Artech House, 1992.
2. R. J. Barker and E. Schamiloglu, *High-Power Microwave Sources and Technologies*, IEEE Press, 2001.
3. C. D. Taylor and D. V. Giri, *High Power Microwave Systems and Effects*, Taylor and Francis, 1994.
4. E. Schamiloglu, K. H. Schoenbach, and R. J. Vidmar, "On the road to compact pulsed power: adventures in materials, electromagnetic modeling, and thermal management," in *Proc. 14th IEEE Int'l Conf. Pulsed Power*, Dallas, TX, June15-18, 2003, pp. 3-8
5. Y. Ye *et al.*, "Influence of Nanocrystalline Grain Size on the Breakdown Strength of Ceramic Dielectrics," in *Proc. 14th IEEE Int'l Conf. Pulsed Power*, Dallas, TX, June 15-18, 2003, pp. 719-722
6. E. Schamiloglu, K. H. Schoenbach, R. Vidmar, "Basic research on pulsed power for narrowband high power microwave sources," in *Proc. SPIE Conf. Intense Microwave Pulses IX*, Orlando, FL, April 1-5, 2002, pp. 1-9
7. S. Xiao *et al.*, "High power water switches: postbreakdown phenomena and dielectric recovery," *IEEE Trans. Dielectrics and Elect. Insul.*, vol. 11, pp. 604-612, Aug. 2004
8. R. Burns, *The life and times of A D Blumlein*, IEE Publishing, 1999
9. S.T. Pai and Qi Zhang, *Introduction to High Power Pulse Technology,* World Scientific, 1995, pp. 82-83, 121-125
10. P.W. Smith, *Transient Electronics: Pulsed Circuit Technology*, Wiley, 2002, pp. 75-80
11. D. M. Pozar, *Microwave Engineering*, Wiley, 1998, pp. 112-113
12. J. A. Alexander *et al.*, "Plastic Laminate Pulsed Power Development," presented at the SAE Power Systems Conference, San Diego, CA, Oct. 2000, Paper 00PSC-113