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COMPUTATIONAL AND EXPERIMENTAL
PROGRESS ON LASER-ACTIVATED GAS
AVALANCHE SWITCHES FOR BROADBAND,
HIGH-POWER ELECTROMAGNETIC PULSE
GENERATION

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Computational and experimental progress on laser-activated gas avalanche switches
for broadband, high-power electromagnetic pulse generation*

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ABSTRACT

The gas avalanche switch, a high-voltage, picosecond-speed switch, has been proposed. The basic switch consists of pulse-charged electrodes, immersed in a high-pressure (7–800 atm) gas. An avalanche discharge is induced in the gas between the electrodes by ionization from a picosecond-scale laser pulse. The avalanching electrons move toward the anode, causing the applied voltage to collapse in picoseconds. This voltage collapse, if rapid enough, generates electromagnetic waves. A two-dimensional (2D), finite difference computer code solves Maxwell's equations for transverse magnetic modes for rectilinear electrodes between parallel plate conductors, along with electron conservation equations for continuity, momentum, and energy. Collision frequencies for ionization and momentum and energy transfer to neutral molecules are assumed to scale linearly with neutral pressure. Electrode charging and laser-driven electron deposition are assumed to be instantaneous.

Code calculations are done for a pulse generator geometry, consisting of an 0.7 mm wide by 0.8 mm high, beveled, rectangular center electrode between grounded parallel plates at 2 mm spacing in air. In one operational mode, a uniform distribution of initial electrons is induced in the gap between the center electrode and the lower plate. With the center electrode at 227 kV positive and 15 atm pressure, voltage pulses of 241 kV, 2 ps rise times, 8 ps full widths at half maximum (FWHM), 30 ps durations, and 24 GHz 3 dB bandwidths are induced at the ends of the plates by passing electromagnetic waves. Similar pulses occur at 292 kV, 27 atm and 3.9 MV, 700 atm. Slower pulses are generated at 49 kV and 8 atm. In another operational mode, delayed laser pulses induce ionization in both the lower and the upper gas gaps. Voltage pulses of reduced FWHMs (1.1–1.8 ps) and amplitudes (7–51 kV) are then generated by interfering electromagnetic waves from the two gaps.

Preliminary voltage holdoff tests with an overvolted series stripline switch, having knife edge to slightly concave cylindrical electrodes and a 102 μm gap, show holdoff times of 2–6 ns. The excitation is an irregular ac charging pulse for conditions up to 56 kV and 14 atm in nitrogen.

1. INTRODUCTION

Recently, a promising candidate for picosecond, high-voltage switching, the gas avalanche switch, was proposed.^{1,2} The basic switch consists of a set of pulse-charged electrodes, immersed in a high-pressure (7–800 atm) gas. An avalanche discharge is induced in the gas between the electrodes by ionization from a picosecond-scale laser pulse. The laser-initiated electrons rapidly avalanche toward the anode in the applied electric field. This rapid avalanche, fueled by the large number of available electrons in the high-pressure gas, causes the applied voltage across the electrodes to collapse in picoseconds. This voltage collapse occurs long before the hot channel formation in a conventional spark gap.

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Several versions of the gas avalanche switch are possible. A simple parallel plate capacitor version consists of a high-pressure gas confined between two parallel metal plates. An analysis of the voltage delay and collapse times for this switch has been done by Villa¹ and Cassell and Villa.² These researchers performed numerical time integration of a zero-dimensional, electric circuit equation based on Kirchoff's laws. This current node equation included a resistively limited charge feed and a constant power supply voltage. This analysis predicted voltage collapse times of several picoseconds for nitrogen and air and 1 ps or less for argon. These results were for a plate spacing or gap of 100 μm .

2. A TWO-DIMENSIONAL, ELECTROMAGNETIC, ELECTRON FLUID CODE

To confirm the encouraging predictions of the circuit analysis mentioned previously, we have developed a 2D computer code, GAS2D, which simultaneously and self-consistently solves Maxwell's equations for transverse magnetic field modes in a gas between two parallel perfect conductors and a set of electron fluid conservation equations. These conservation equations are for continuity, momentum, and energy. One or more rectilinear, perfectly conducting electrodes may be placed between the plates.

2.1 Governing equations

For a free space dielectric between the plates, the relevant Maxwell's equations in the MKS system are

$$\frac{\partial E_x}{\partial t} = \frac{1}{\epsilon_0} \frac{\partial H_z}{\partial y} - \frac{nev_x}{\epsilon_0}, \quad (1)$$

$$\frac{\partial E_y}{\partial t} = -\frac{1}{\epsilon_0} \frac{\partial H_z}{\partial x} - \frac{nev_y}{\epsilon_0}, \quad (2)$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu_0} \frac{\partial E_x}{\partial y} - \frac{1}{\mu_0} \frac{\partial E_y}{\partial x}, \quad (3)$$

where E_x is the electric field component in the x direction, E_y is the electric field component in the y direction, H_z is the magnetic field component in the z direction, ϵ_0 is the free space permittivity, n is the electron density, e is the electron charge (1.6×10^{-19} C), v_x is the electron velocity in the x direction, v_y is the electron velocity in the y direction, and μ_0 is the free space permeability.

The electron fluid equations are

$$\frac{\partial n}{\partial t} = nv_i, \quad (4)$$

$$\frac{\partial(nv_x)}{\partial t} = \frac{neE_x}{m} - nv_m v_x, \quad (5)$$

$$\frac{\partial(nv_y)}{\partial t} = \frac{neE_y}{n} - nv_m v_y, \quad (6)$$

$$\frac{\partial(nU)}{\partial t} = ne (E_x v_x + E_y v_y) - nv_u(U - U_0) - nv_i \epsilon_i, \quad (7)$$

where v_i is the ionization collision frequency, m is the electron mass, v_m is the electron to neutral molecule momentum transfer frequency, U is the electron kinetic energy, v_u is the electron to neutral energy transfer frequency, U_0 is the average neutral energy, and ϵ_i is the average neutral ionization potential. The equations are specialized to air by taking $U_0 = 0.025$ eV and $\epsilon_i = 14$ eV. The electron distribution function is assumed to be Maxwellian. We neglect convection, magnetic forces, pressure gradients, and heat flows. We ignore electron losses due to atomic and molecular processes, such as attachment and recombination, as well as diffusion. Electron generation by photoionization is also neglected.

The collision frequencies used in the code for air are analytic fits to two kinds of data. Below electron energies of 150 eV, the data is from electron swarm measurement; whereas, above 150 eV, the data is from theoretical calculations with a Maxwellian velocity distribution.^{3,4} These collision frequency fits are those previously used for microwave breakdown in low-pressure air^{5,6} and microwave propagation in the earth's atmosphere.⁷⁻⁹ These collision frequencies are assumed to scale directly with neutral pressure.

In addition, electron pulse charging is assumed to occur instantly so that the real experimental problem of premature breakdown from effects, such as field emission or surface flashover, is ignored. Also the laser deposition of initial electrons is presently assumed to be instantaneous. We thus ignore detailed modeling of the laser ionization.

2.2 Computational geometry

Figure 1 shows the geometry for computational solution of the governing equations. The coordinate system is a 2D, rectangular, x - y system. The coordinate z extends out of the plane of the figure. The space between the parallel metal plates at $y = 0$ and $y = +g$ is partitioned by a rectangular mesh. Solution points for the electromagnetic variables are located to create a staggered solution grid. Similar grids have resulted in convenient spatial differencing of Maxwell's equations in 2D, explicit, finite difference, electromagnetic scattering codes.¹⁰ As denoted in the box at the bottom of Fig. 1, E_x is solved at even grid points along odd horizontal (x - z) planes. The lowermost of these planes coincides with the bottom metal plate; whereas, the uppermost coincides with the top metal plate. Since these plates are perfect conductors, E_x is zero along them. E_y is calculated at odd grid points along even horizontal planes, and H_z is calculated at even grid points along the same planes. The electron fluid variables, n , v_x , v_y , and U , are evaluated at the grid points for H_z . A rectangle of grid points, consisting of those for E_x , E_y , H_z , and the unallocated grid point directly beneath that for E_y , constitutes a grid cell. The lower left grid cell, which includes the coordinate origin in Fig. 1, is replicated in the x and y directions to complete the finite difference grid.

2.3 Numerical solution

The spatial derivatives in Eqs. (1)–(3) are replaced with central finite differences. The left-hand sides of Eqs. (5)–(7) are rewritten as time derivatives of v_x , v_y , and U . Seven ordinary differential equations (ODEs) in time then result for each cell of four grid points. The global set of ODEs for all the grid cells is solved by time integration with the block-iterative, optionally stiff, implicit, variable step solver GEARBI.¹¹

GEARBI has several attractive features for problems involving gas breakdown and electromagnetic wave propagation. The variable integration step allows reduction of problem solution time, as compared to a fixed step solver set at a small step for good solution resolution. During periods of rapid avalanche ionization, the code with GEARBI can take small time steps of the order of the inverse of the ionization rate. After the ionization slows down significantly or ceases, the code can speed up, using larger time steps. In the case of electromagnetic wave propagation, these steps can somewhat exceed the Courant limit. The Courant limit for stability of Maxwell's equations with explicit finite differencing is the time step limit

given by $\Delta t_1 = \Delta x/c$ in one dimension and $\Delta t_2 = (\Delta x^2 + \Delta y^2)^{1/2}/c$ in two dimensions.^{10,12} The quantity Δx is the grid spacing in x direction, Δy is the grid spacing in the y direction, and c is the speed of light in vacuum. For a given computer, the block-iterative treatment allows solution of larger problem grids than is possible with other types of treatment because the memory requirement is less. For the gain in grid size, more time and effort must be invested to create the required user-supplied subroutines. The stiff equation system option also allows some highly significant reduction of

Fig. 1. Solution geometry for the electron fluid code.

problem solution time, since it causes the solver largely to ignore low-amplitude, high-frequency oscillations in the solution.

3. MODELING PARALLEL PLATE CAPACITOR SWITCHES

The 2D electron fluid code was first applied to a parallel plate capacitor switch with a gap of $100\text{ }\mu\text{m}$, an applied voltage of 266 kV , and a pressure of 350 atm . The results of these calculations agreed extremely well with the predictions of the circuit code.^{13,14} The electron drift velocity from these 2D calculations agreed well with experimental results for the range, $0.1 \leq E/p \leq 16\text{ V/(cm-torr)}$, where E is the electric field between the plates in V/cm , and p is the pressure in torr. In addition, the α/p from the 2D code results was in good agreement with experimental results for the range, $46 \leq E/p \leq 100\text{ V/(cm-torr)}$. The quantity α is the first Townsend coefficient. These favorable comparisons with experimental results give confidence in the soundness of both codes.

4. A SIMPLE PULSE GENERATOR SWITCH

A gas avalanche switch, which is slightly more sophisticated than the parallel plate capacitor switch, may be made by placing a center electrode between the plates of the parallel plate capacitor switch. This new version is suitable for a pulse power linac or a pulse generator. When a properly configured center electrode is charged to a suitable high voltage with a suitable gas pressure, this switch is predicted to produce electromagnetic pulses with picosecond rise times and durations.¹³⁻¹⁵

Figure 2 shows a simple model for such a switch. The parallel plates at the top and bottom of the figure are initially at ground potential. The pressure of the air between the plate is from $7\text{--}700\text{ atm}$. A rectangular electrode with bevelled corners is centered between the parallel plates and charged to a positive high voltage V_0 . The gap between this center electrode and the bottom plate is uniformly filled with 1.7×10^{13} laser-induced electrons for an assumed depth of 1 m

Fig. 2. The pulse generator switch model.

perpendicular to the plane of the figure. This gap is the lower gap. The space between the center electrode and the upper plate is the upper gap. For center electrode voltages from 227 kV to 3.90 MV, computations predict that this geometry produces electromagnetic waves of about 10 ps FWHM and 20 GHz bandwidth. The range of voltage for production of these pulses is most likely even greater, as long as the air pressure scales properly. The waves propagate outward from the center electrode to the left and right boundaries of the figure.

The solution space extends from 3.45 mm to the left of the center electrode vertical center line to 3.50 mm to the right of that line. Transverse electromagnetic (TEM) mode boundary conditions are imposed at the left and right free space boundaries to minimize the amplitude of any inwardly traveling reflected waves, which may be generated at these grid boundaries by the outwardly traveling waves. At the left boundary, the imposed condition is $E_y = \eta H_z$, where η is the free space intrinsic impedance, $(\mu_0/\epsilon_0)^{1/2}$. At the right boundary, the conditions are $H_z = E_y/\eta$ and $E_x = 0$. On the vertical faces of the perfectly conducting center electrode, $E_y = 0$. On the horizontal faces, $E_x = 0$.

The finite element electrostatic code STAT2D gives the initial electric field distribution. This distribution is used as the initial electric field conditions for the electron fluid code simulations. Figure 3 shows the initial distribution of E_y . The region of zero electric field at the center of the x-y plane corresponds to the center electrode. As specified by the boundary conditions, E_y is zero along the two vertical faces of the center electrode. Initially, the absolute value of E_y is greatest along the two horizontal faces. Along these faces, the absolute value of E_y peaks near the corners, since these are the regions of greatest electric field enhancement. In addition, E_y is negative below the horizontal center line of the center electrode and positive above it.

5. PULSE GENERATION AT KILOVOLT VOLTAGES

When the computer code simulation starts with the applied voltage on the center electrode at 292.4 kV and the air pressure at 27.2 atm, the voltage between the center electrode and the lower plate drops toward zero in about 3 ps. This behavior is shown in Fig. 4, which displays the waveform of the voltage between the center electrode and the lower plate close to the vertical center line in Fig. 2. This waveform begins negative because the potential of the lower plate is referred to that of the center electrode. After rebounding slightly more negative at 4 ps, this voltage slowly drops off to zero at 28 ps. This voltage ends up slightly positive at the termination of the simulation at 36.5 ps.

Fig. 3. Initial distribution of E_y .

Fig. 4. Waveform of the voltage between the center electrode and the bottom plate near the vertical center line.

This initially rapid voltage collapse is caused by a large, rapidly increasing flow of avalanche electrons toward the center electrode. This current generates electromagnetic waves, which propagate out to the left and right boundaries. The E_y component of the waves is shown in Fig. 5 at 11.0 ps into the simulation. In the near x - E_y plane, which corresponds to the surface of the lower parallel plate, two positive waves have moved out to the free space boundaries. The fronts of these waves have just hit the boundaries. This impact can be seen in Fig. 6, which shows the waveform of the voltage, $\int_0^g E_y dy$, between the parallel plates at the right boundary. The wave crests at lower plate hit the boundaries later at about 14.5 ps. This time slightly precedes the first voltage peak in Fig. 6 at 15 ps. Discernible wave crests develop at the far x - E_y plane, which corresponds to the surface of the upper plate, at about 12 ps. These upper plate crests hit the free space boundaries at about 16 ps, slightly before the second peak in Fig. 6 at 16.5 ps. Since the voltage between the plates is the integral of E_y , its peaks do not quite correspond in time to the incidence at the boundaries of the E_y wave crests along the plates. As one moves from the lower plate toward the upper plate in Fig. 5, the wave crests for fixed y lag behind the wave crests at the lower plate.

The curious bipolar spikes between the center electrode and bottom plate are believed to be noise from the initial H_z component. This component appears around the center electrode during the first time step of the simulation. The E_x and E_y field components calculated by STAT2D at the center electrode boundary are thought to be inaccurate, since they are extrapolations of spatial derivatives of the electric scalar potential determined at the finite element Gauss points. The use of spatial derivatives of these inaccurate field components in Eq. (3) causes even more aggravated inaccuracies. These inaccuracies result in imperfect cancellation of the right-hand terms in Eq. (3). This imperfect cancellation of terms gives a time derivative for H_z all around the perimeter of the center electrode at zero time, which is not zero. This leads to checkerboard-like noise in H_z all around the boundary of the center electrode at 0.5 ps, the second output time. This noise

Time = 1.1000×10^{-11} sec

Fig. 5. E_y at 11 ps.

Fig. 6. Voltage waveform at right boundary at 292.4 kV and 27.2 atm.

extends well into the upper gap toward the upper plate. This disturbance thus appears in the upper gap long before it could physically propagate from the lower gap, where the electron avalanching occurs.

In addition to strong waves in E_y and ηH_z with amplitudes of the order of 2×10^8 V/m, weaker waves in E_x with amplitudes of the order of 5×10^7 V/m also propagate out from the center electrode in complicated patterns. These E_x waves are probably generated by the vertical variation of the electric field in the lower gap during the avalanche, the 2D nature of the center electrode, and the dynamic vertical variation of H_z . The generation, propagation, and reflection of waves around the center electrode are quite complicated. These effects must cause the lag of the E_y wave crests in the far x - E_y plane with respect to those in the near x - E_y plane. Since E_x is dynamic, the generated mode structure is not purely TEM.

As shown in Fig. 6, the peak pulse voltage is 300.2 kV, the 10–90% rise time to the peak pulse voltage is 2.41 ps, the FWHM is 9.11 ps, and the pulse duration is greater than 26 ps. A slight negative precursor precedes the positive pulse. Of the initial electrostatic energy of 3.34 J/m, 55.4% has crossed the free space boundaries by 36.5 ps. The peak pulse voltage is a 2.67% enhancement of the applied voltage on the center electrode. The tail on the voltage pulse appears to be due to the slow decay of the electric field in the upper gap. Figure 7 shows the frequency spectrum of the voltage pulse in Fig. 6. The spectral peak is at dc, and the 3 dB bandwidth is 23.94 GHz under the assumption that the voltage pulse drops discontinuously to zero at 36.5 ps.

Very similar results occur at 227 kV on the center electrode with the air pressure lowered in direct proportion to the voltage.¹⁵ This scaling of the pressure keeps the initial nominal E/p at the center electrode constant. Reduction of this nominal E/p causes a lengthening of the induced voltage pulse rise time, FWHM, and duration. Increase of this quantity causes an increase in the peak pulse voltage and some reduction in the rise time and FWHM. At 17 atm, the rise time is 2.56 ps, the FWHM is 8.98 ps, and the peak pulse voltage is 236.6 kV. At 1 atm, the rise time is 1.51 ps, the FWHM is 7.12 ps, and the peak pulse voltage is 277.7 kV. Several induced voltage pulse characteristics for the center electrode voltage at 227 kV are shown in Table 1 for variation of the air pressure from 17–1 atm.

Fig. 7. Frequency spectrum of the voltage at 292.4 kV and 27.2 atm.

Table 1. Variation of right side voltage pulse characteristics with air pressure at 227 kV center electrode voltage.

Air pressure (atm)	Rise time (ps)	FWHM (ps)	Peak voltage (kV)
17	2.56	8.98	236.6
15	2.28	8.38	240.5
7	1.87	7.57	264.2
1	1.51	7.12	277.7

6. PULSE GENERATION AT MEGAVOLT VOLTAGES

Induced voltage pulses with similar characteristics also occur with 3.889 MV on the center electrode and 700 atm pressure. Figure 8 shows the right side induced voltage waveform as the solid curve. The rise time is 2.04 ps, the FWHM is 7.88 ps, the peak voltage is 4.769 MV, and the duration is greater than 20.5 ps. The peak voltage represents a 22.6% enhancement of the applied voltage. By 29.5 ps, 71.4% of the initial electrostatic energy has crossed the boundaries. With the assumption of an abrupt drop of the pulse voltage to zero at 29.5 ps, the bandwidth is 29.8 GHz.

When the initial, laser-activated electrons are concentrated into a more narrow column, a higher peak voltage occurs at the right boundary. The dashed curve in Fig. 8 shows the voltage waveform for such a case. In this case, 1.2×10^{12} initial electrons uniformly fill a 50 μm wide column, which bridges the center electrode and the lower plate. This narrow column is centered on the vertical center line in Fig. 2. The rise time of the dashed curve is 1.72 ps, the FWHM is 7.39 ps, and the peak pulse voltage is 5.378 MV. This peak voltage is a 38.3% enhancement of the applied voltage. In this case, 82.9% of the initially stored electrostatic energy crosses the boundaries by 29.5 ps. The bandwidth is 30 GHz.

Fig. 8. Voltage waveforms at the right boundary for 3.889 MV and 700 atm.

7. THE GENERATION OF LONGER PULSES BY VOLTAGE DETUNING

It is possible to lengthen the FWHM and the duration of the induced voltage pulses from this gas avalanche switch by decreasing the applied voltage at a fixed pressure. Figure 9 shows a right side voltage waveform for 48.8 kV and 8 atm pressure. The rise time is 14.7 ps, the FWHM is 28.9 ps, the duration is slightly greater than 109 ps, and the peak voltage is 18.54 kV. The bandwidth is 9.28 GHz. The peak value of this pulse is 38.0% of the voltage applied to the center electrode.

Table 2 compares voltage pulse characteristics for three center electrode voltages at roughly constant air pressure. Detuning of the applied voltage dramatically lowers the amplitude of the pulse.

Table 2. Variation of right side voltage pulse characteristics at roughly 8 atm air pressure.

Applied voltage (kV)	Air pressure (atm)	Rise time (ps)	FWHM (ps)	Pulse duration (ps)	Peak voltage (kV)	Bandwidth (GHz)
227	7	1.87	7.57	>15.5	264.2	39.6
48.8	8	14.7	28.9	>109	18.5	9.28
24.4	8	70.1	167	>385	1.71	1.71

8. THE GENERATION OF SHORTER PULSES BY WAVE INTERFERENCE

8.1 Pulse width reduction by pressure reduction

It is possible to reduce the voltage pulse FWHM by reducing the pressure at a fixed voltage. Reduction in pressure reduces the voltage collapse time under the center electrode by making the initial E/p greater and the avalanche more rapid. This voltage collapse time is limited at lower pressures by the reduced number of available electrons in the gas.

Fig. 9. Voltage waveform at the right boundary for 48.8 kV and 8 atm.

Calculations show that the reduction in FWHM caused by decreasing the pressure is relatively modest. Table 1 shows that a reduction in pressure from 17 to 1 atm produces a reduction in FWHM of 1.86 ps or 21%.

8.2 Pulse width reduction by size reduction

Another limit on the pulse width must be imposed by the size of the physical structure. The delay in the arrival of the wave crests along the upper and lower plates partly determines the pulse width. This delay is probably given by a path difference like that from point A to point B to point C and back to point B in Fig. 2. This trajectory is indicated in the figure by the arrowheads at the left side of the center electrode. The path difference just defined has a delay given by $\tau = [h + 2((w/2)^2 + g_u^2)^{1/2}]/c$. The quantity $h = AB$ is the height of the center electrode, w is the width of the center electrode, and g_u is the electrode to upper plate gap. Substitution of the correct dimensions gives $\tau = 7.3$ ps. Thus the size of the center electrode and the plate spacing seem to limit the pulse width. Reduction in these dimensions should give a reduction in pulse width.

8.3 Pulse width reduction by wave interference

There appears to be a way to reduce the voltage pulse FWHM without reducing the air pressure or the dimensions of the structure. This way is to trigger the upper gap slightly after the lower gap. If the avalanches in the two gaps are fairly similar, a roughly equal amplitude, negative polarity electromagnetic wave will occur at the upper gap. With no time delay in the initiation of avalanching in the two gaps, the two electromagnetic waves from the gaps should cancel almost completely at the free space boundaries. This cancellation should produce very small voltage pulses at the boundaries. With initiation of the upper gap delayed slightly from initiation of the lower gap, the wave from the upper gap should cancel only the tail of the wave from the lower gap. The width of the voltage pulse should therefore be reduced by electromagnetic wave cancellation or interference.

Figure 10 shows two right side voltage pulses generated by wave interference with two different delays between laser initiation of the two gaps. Equal numbers of electrons (1.7×10^{13} electrons/m depth) uniformly fill each gap. The center electrode voltage is 227 kV, and the pressure is 15 atm. When the delay is 0.5 ps, the waveform at the left of Fig. 10 occurs. This pulse has an amplitude of 51.1 kV and a FWHM of 1.79 ps. It has a very slight negative precursor and a

Fig. 10. Voltage waveforms generated by wave interference.

noisy trailing tail of about 7 kV amplitude. This tail amplitude is about 14% of the pulse amplitude. The pulse amplitude is 22.5% of the applied voltage. Thus, the price of a shorter main pulse is a dramatic reduction in amplitude. The frequency spectrum of this waveform is shown at the left of Fig. 11. The 3 dB bandwidth is 113.3 GHz. This value is fortuitously large because the spectral cut off values fall just below the spectral dips at about 60 and 100 GHz.

A delay of 0.1 ps for the same conditions produces the pulse at the right of Fig. 10. Because of the stronger interference, this pulse has a lower amplitude of 6.93 kV and a shorter FWHM of 1.14 ps. The time scales of the two waveforms in Fig. 10 are slightly different. Unfortunately, the shorter pulse has a stronger negative precursor of about -2 kV and a much more prominent trailing signal. This trailing signal has an amplitude of about 5.3 kV or 76.5% of the peak value of the pulse. The peak value of the pulse is now only 3.05% of the applied voltage. The spectrum of this waveform is shown at the right of Fig. 11. The bandwidth is 28.09 GHz. Strong attenuation of the trailing signal will greatly increase the bandwidth.

9. PRELIMINARY EXPERIMENTAL MEASUREMENTS

Experimental work on gas avalanche switches has, so far, concentrated on the demonstration of picosecond switching speeds with a stripline with a series gap in it.^{16,17} This switching gap is excited by a high-voltage pulser. The gap is between a knife edge electrode and a plane electrode with a slightly concave contour to it. The knife edge electrode is the anode, in order to minimize field emission in the high electric field region. The switching gap is variable in length. The stripline is secured to a metal boat, which slides into a pressure vessel. The pressure vessel has two electrical feed-throughs, a set of gas fittings, and an optical port for laser illumination of the gap.

To date, only preliminary voltage holdoff tests without laser illumination have been performed. Figure 12 shows curves of the breakdown voltage threshold versus gas pressure for a 102 μm electrode spacing. Both dc and an irregular ac pulse are used for excitation. For the pulse, breakdown occurred 2–6 ns after application. The top pair of curves in Fig. 12 is for the pulsed excitation. The upper of this pair of curves is for nitrogen; the lower is for argon. The bottom pair of curves is for dc. Once again, the top curve of the pair is for nitrogen. The bottom curve is for argon. The peak dc voltage shown is 15 kV at 13.6 atm. The peak pulsed voltage shown is 56 kV at 13.6 atm. Higher pressures should give higher voltage thresholds.

Fig. 11. Voltage spectra generated by wave interference.

Fig. 12. Threshold voltage versus gas pressure for the stripline gap at 102 μm .

10. CONCLUSIONS

The simple, laser-activated, air gas avalanche switch computationally shows great promise for the production of high voltage (227 kV–4 MV), broadband (20 GHz), electromagnetic pulses of picosecond rise time and duration. With fixed dimensions, the FWHM of the induced voltage pulse may be shortened to 1.14 ps by the wave interference technique. The FWHM also may be lengthened to 167 ps by low-voltage detuning at a fixed air pressure.

The conclusive experimental verification of these predictions remains, however, presently undemonstrated.

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