United States Patent [19]

Tidman

[11] **3,775,638**

[45] **Nov. 27, 1973**

[54] **ESTABLISHING HIGHLY CONDUCTIVE PATH IN GAS BY THERMAL GUIDANCE OF DISCHARGE**

[75] Inventor: **Derek A. Tidman,** Silver Spring, Md.

[73] Assignee: **Versar Inc.,** Springfield, Va.

[22] Filed: **Mar. 27, 1972**

[21] Appl. No.: **238,506**

[52] **U.S. Cl.**..... **315/36,** 219/121 LM, 307/149, 315/149, 331/94.5

[51] **Int. Cl.**..... **H02h 7/24,** B23k 27/00, H01s 3/00

[58] **Field of Search**..... 315/36, 149, 150, 315/151, 152, 153, 154, 155, 156, 157, 158; 331/94.5; 307/149; 200/152 R; 219/121 L

[56] **References Cited**

UNITED STATES PATENTS

3,404,403	10/1968	Vallese et al.	331/94.5 X
3,524,101	8/1970	Barbini	315/150

OTHER PUBLICATIONS

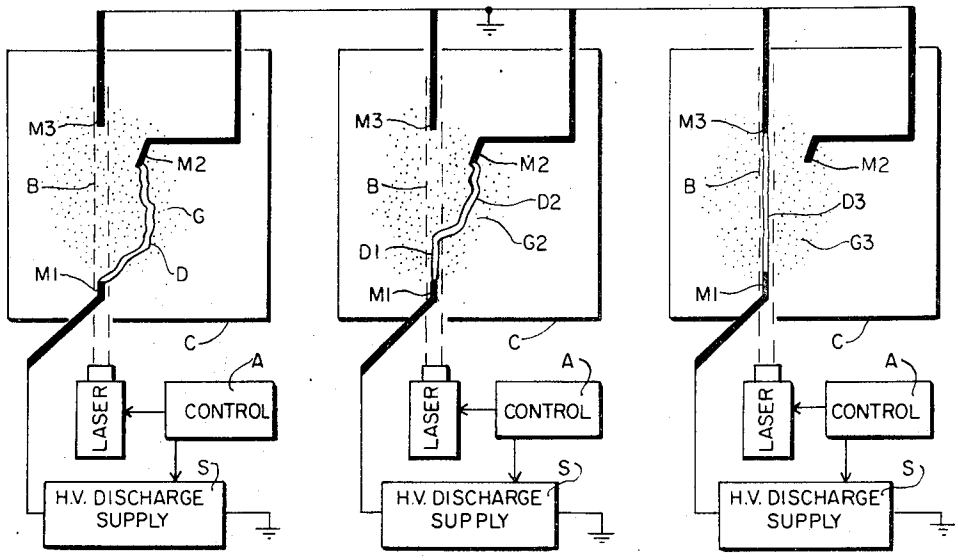
Conduction Via Tracks Ionized by a Laser by J. L. Anderson, IBM Technical Disclosure Bulletin, pp. 71 & 72, Vol. 5, No. 12, May 1963.

Primary Examiner—Roy Lake
Assistant Examiner—Hugh D. Jaeger
Attorney—Arthur E. Dowell, Jr. et al.

[57] **ABSTRACT**

The apparatus and methods in which a laser beam or other light source of comparable steradiancy is employed to establish an initial low-density rarefaction trail through a gas medium by expanding the gas within the trail to a lower density, and then discharging an auxiliary high voltage source therethrough to ionize that initial trail to a high level, whereby to form a highly conductive path through which useful amounts of electrical energy can be conducted in a straight line, for instance, for the transmission of intelligence or power.

18 Claims, 11 Drawing Figures



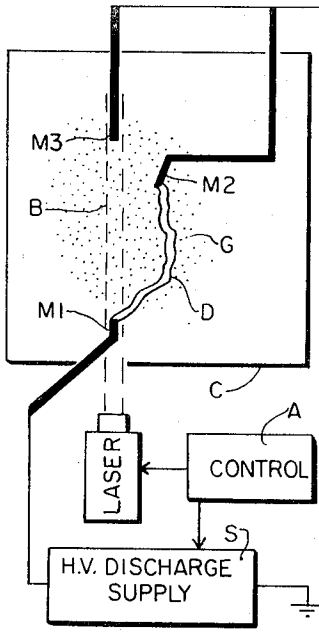


Fig. IA

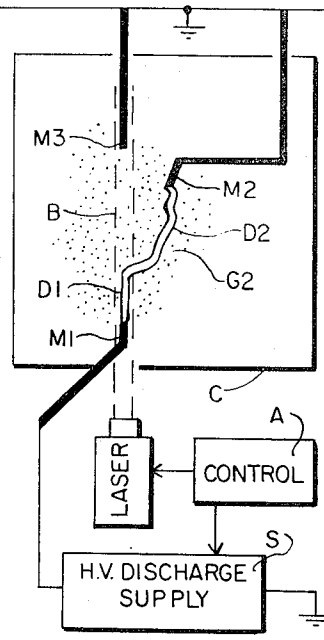


Fig. IB

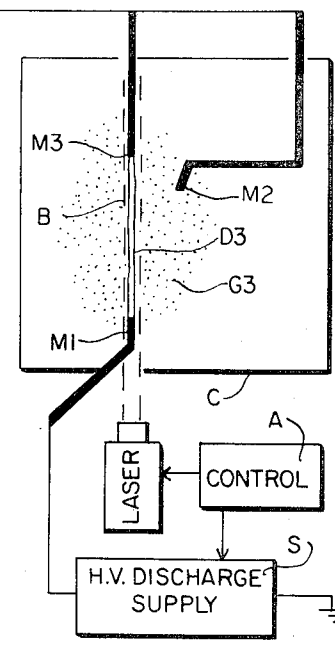


Fig. IC

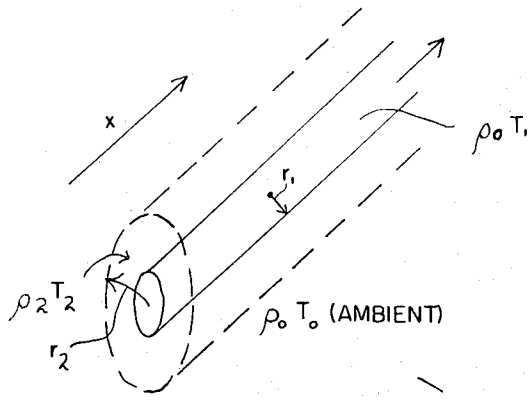


Fig.2

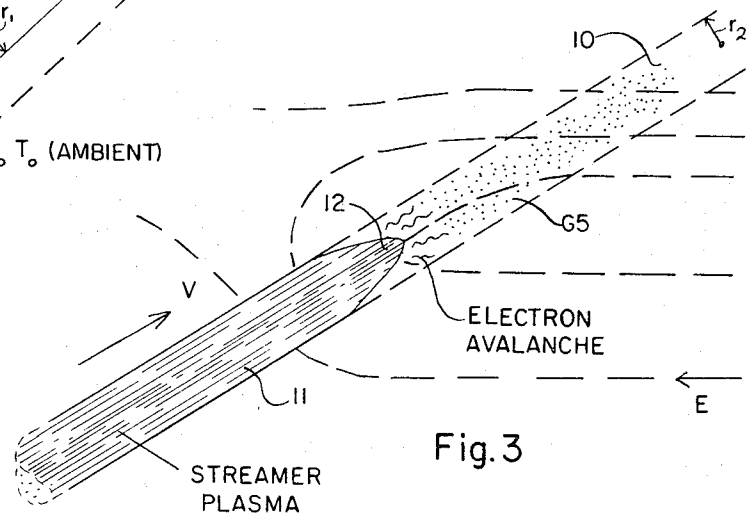


Fig.3

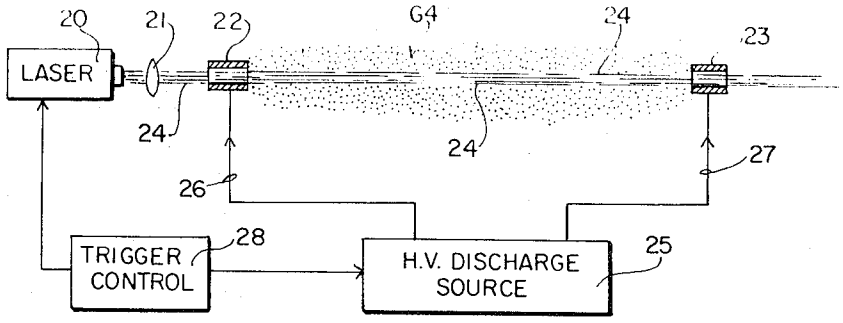


Fig. 4

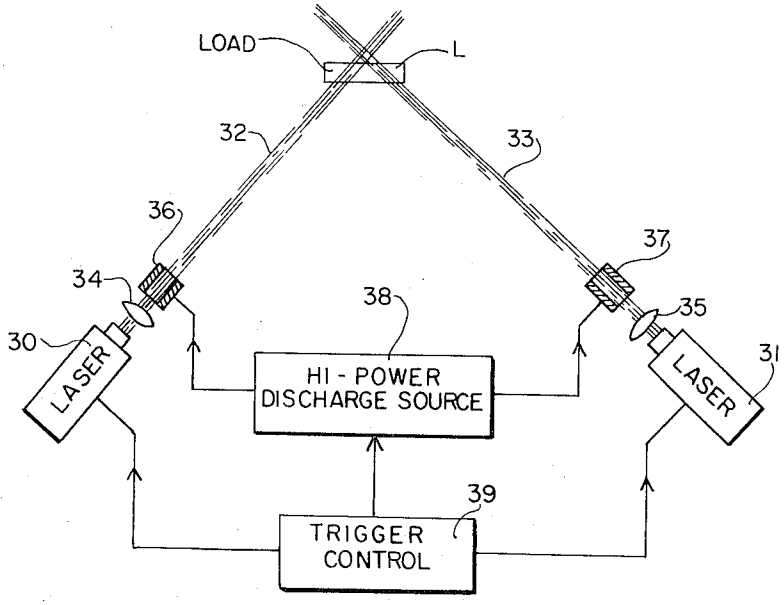


Fig. 5

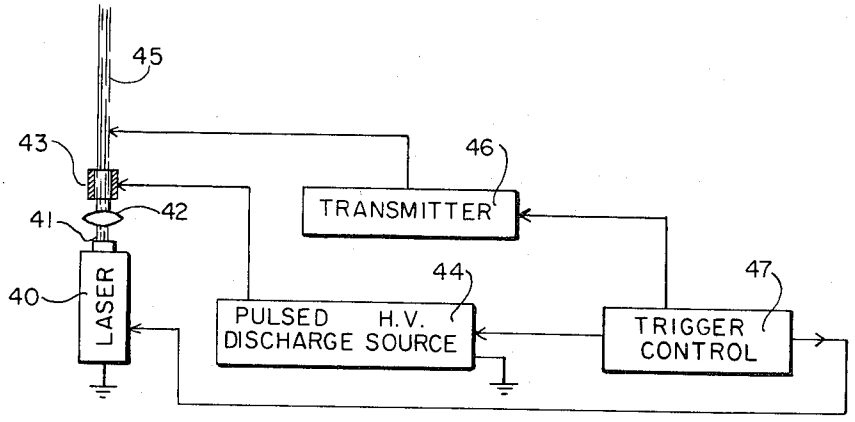


Fig. 6

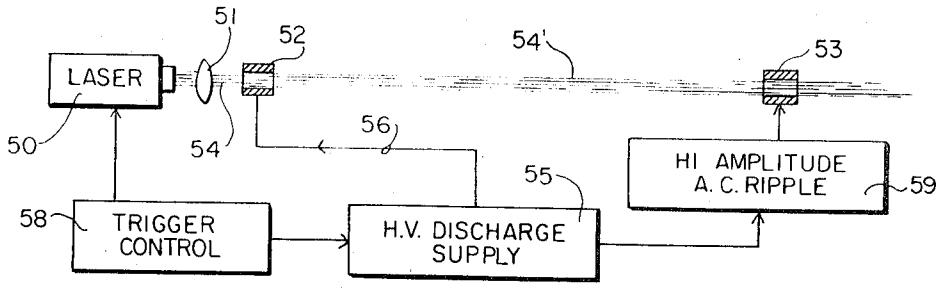


Fig. 7

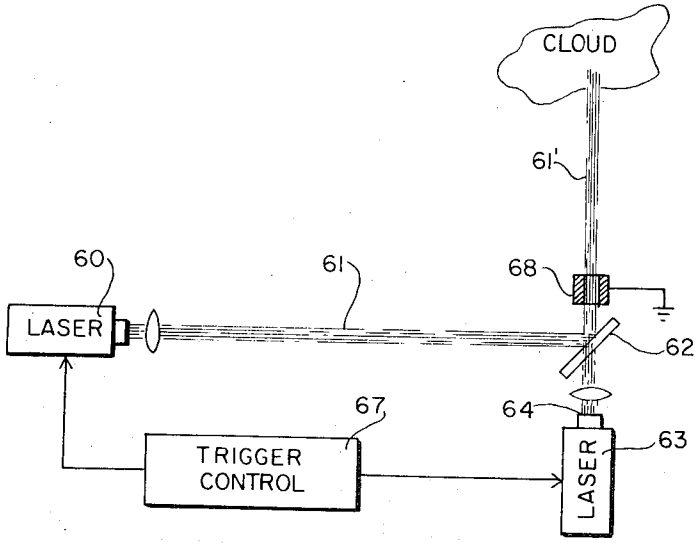


Fig. 8

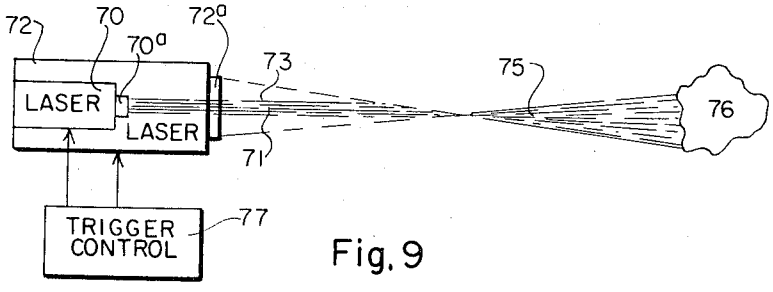


Fig. 9

ESTABLISHING HIGHLY CONDUCTIVE PATH IN GAS BY THERMAL GUIDANCE OF DISCHARGE

This invention relates to improvements in laser beam methods and systems wherein the beam is passed through a gas medium for the purpose of establishing a long, straight, well defined trail of density which is temporarily diminished with respect to the ambient gas density. An auxiliary means is then employed to discharge a high voltage breakdown streamer through this trail, producing a long, straight, highly-conductive path through the gas.

There are seveal approaches that can be resorted to for the purpose of lengthening and straightening the discharge of energy through a dense gas, for example at atmospheric pressure. One approach is that set forth in a copending application, Ser. No. 27,369 filed Apr. 10, 1970 in the name of Jack Roy Vaill and entitled "Laser Beam Techniques", now U.S. Pat. No. 3,719,829 wherein methods and means are described by which an initial partially-ionized trail is laid down through the gas by a laser beam to provide in the trail a degree of conductivity capable of lengthening the path through which a high voltage auxiliary source can then be discharged.

The present disclosure teaches another, substantially different, approach by which an analogous purpose can be accomplished but using another basis for achieving a lengthened straight-line breakdown path. The present approach does not seek to render the initial laser trail more conductive by ionization, but rather it seeks to suddenly heat the gas in a well defined essentially-cylindrical trail so that the density within that trail suddenly decreases, and then discharge an auxiliary high-energy source through that low-density trail, which serves as a preferred breakdown path, before subsequent cooling of the trail can restore the initial density within the trail, the latter occurring slowly as compared with the propagation rate of the laser beam and of the auxiliary source discharge. The present approach is based upon the well known fact that as a gas density is reduced, the breakdown length of a given voltage therethrough becomes longer and longer in an essentially linear relationship, at least until the density reaches an extremely low-level, for instance, 0.005 atmospheric density for air which is well below the densities being considered herein. This phenomenon is known as the Law of Paschen, and is expressed graphically in terms of Paschen Curves, which will be further discussed hereinafter.

It is accordingly a principal object of the invention to provide an improved method and system for establishing in a dense gaseous medium a long, straight path which is highly ionized and can be used as an efficient conductor. It is a more specific object of this invention to use a laser beam to establish in the gas an initial long straight low-density trail which is not substantially ionized, and to use this low-density trail to guide an electrical discharge along the low density trail established by the initial laser beam to achieve said highly ionized path. The breakdown path length and velocity of the electron avalanche, i.e. the ionizing potential wave which establishes the electrical discharge when driven by a given voltage source, increases with decreasing density in the region of normal atmospheric gas densities and thus gives rise to guidance of the discharge along the low density trail. After the passage of the ionizing potential wave, the ion concentration in the trail will have been increased from an ambient level, perhaps of a few ions per cubic centimeter, to a much greater level, perhaps to substantially complete ionization, i.e., in the range of 10^{19} ion/cc at atmospheric pressure. At this latter concentration, the path resistance per unit length would be measured in terms of a few ohms per meter or less, depending on the radius of the ionized channel.

"Laser means" as used herein includes not only presently known lasers as such, but also other radiation sources of high steradiancy which will impart energy to a gas, thereby heating the gas and causing a lowering of the gas density along a well defined trail.

A laser beam of suitable wavelength can penetrate through a gas medium over great distances, and to the extent that its energy is absorbed thereby the gas will experience a transient increase in temperature and a transient decrease in density in the resulting trail. On the one hand, where a certain length of heated trail thus produced must be achieved, the rate of absorption of the laser energy per unit length of the trail must be carefully selected so as not to be too great, because too high a rate of laser-energy absorption by the gas will cause too rapid absorption in the initial portion of the trail resulting in attenuation of the energy to a high degree, not only unduly shortening the heated trail but also causing other effects such as gas ionization in the trail to occur. Such ionization effects tend to make the gas more opaque to the passage of the laser beam. Conversely, if the absorption of energy by the gas in the trail is at too low a rate per unit length, then the reduction in the density of the gas due to heating will be too small to provide guidance and lengthening for a subsequent electrical discharge. Between these extremes, the path of the electrical discharge will be optimumly guided and lengthened by the low density laser-induced trail.

While the guidance effect described above can be achieved using a laser operating in the continuous mode, increased discharge range can be realized for the same auxiliary potential source by operating the laser in the pulsed mode. By pulsing the laser, a higher peak energy can be imparted to the gas and this discharge can be done so rapidly that the heated gas does not have enough time to change its index of refraction during the passage of the laser pulse. Therefore, the defocusing effect, for instance of heated air on the laser beam, is at least partially avoided due to the very brief presence of the beam, and this effect therefore does not diffuse or dissipate the energy significantly in the laser beam, which would otherwise restrict its useful range. Instead, the temperature and pressure of the gas within the beam first rise, and then, as the pressure equilibrates with the pressure of the surrounding gas the gas expands and the high temperature remaining in the trail produces the low gas density required for guidance. Therefore a desirable, but not a necessary attribute of the laser pulse is that it be of a time duration no greater than the acoustic transit time of a compressional wave across the radius of the beam. Other attributes of the laser will be discussd hereinafter.

Although the present technique of using auxiliary means for laying down an initial low density trail can be applied to either CW or pulsed laser systems, or to systems combining both types, the pulsed type has several advantages. In the first place, the pulse system can achieve greater distances, as described above. In the

second place, as time progresses from the initial application of the laser energy to the gas, the low density gas trail will tend to lose its straight line configuration due to thermal convection existing in the gaseous medium near the heated trail, and perhaps even due to motions in the gas due to windage. This convection is generated by the buoyancy of the heated gas, and will be more serious for a horizontal configuration of the beam than for a vertical configuration. Therefore, especially in the horizontal configuration, alternate periodic re-establishing and extinguishing of the path by a pulsed system is beneficial, since it allows the previously heated gas trail to dissipate and die out so that a new straight trail can be re-established in a controlled and highly defined manner.

The laser beam used to establish the low density trail should be selected with regard to energy density, pulse duration and wavelength, so that it provides neither too great nor too little energy deposition per unit length of trail. In order to make any selection, it is necessary to select the gas medium and the trail length first. Having selected a gas, its spectroscopy will provide the information from which laser wavelength can be selected. Optimum pulse duration has already been discussed above. The rate of light energy absorbed in a gas medium is measured by a quantity referred to as the "absorption length". This is the length in the medium the traverse of which absorbs the energy in the laser beam to a level of $1/e$, $e = 2.72$. For greatest efficiency, the desired discharge trail length should be of the same order as the absorption length. The absorption length in any gas varies with the wavelength of the laser radiation. In air it is of the order of one million centimeters in the visible region of the spectrum and on into the near infrared to wavelengths of approximately one micron. For wavelengths from one micron to eight microns, the absorption length is highly variable, depending on the specific spectral absorption line of the constituents of the atmosphere, and in a strongly absorbing region the absorption length may drop to less than 1,000 cm. Above the eight microns, the atmosphere exhibits another low absorption window, with absorbing lengths again reaching 10^6 cm. The atmosphere then starts to absorb strongly in the 11 to 12 micron region and above. These variations allow the selection of optimum laser wavelength so that the gas absorption length can be matched to the desired range for a particular application. For example, a CO_2 laser produces energy at 10.6 microns, and atmospheric air has an absorption length of about 10^6 centimeters at this wavelength, thereby providing a useful range of the order of ten kilometers. The gas medium can of course be doped with other gaseous components to change its absorption length with respect to any particular laser beam wavelength. Specific examples are discussed hereinafter.

The proper matching of wavelength and absorption length will insure that most of the laser beam energy will be usefully converted to heat over the desired length of trail, rather than dissipating too much energy early in the trail which causes excessive ionization, or else leaving too little energy available for dissipation in the remainder of the trail. Proper matching of absorption length and trail length also avoids the inefficient dissipation of only a small fraction of the laser energy over the whole portion of the trail length in which one is interested. After proper matching of absortion length and trail length, then the laser energy level can be set to provide enough heating in the trail to achieve the desired electrical discharge guidance and path lengthening.

As stated above, it is undesirable that the energy put into establishing the initial laser trail should result in substantial ionization of the gas beyond its ambient level since this ionization tends to make the gas opaque to the laser beam. At first it seems desirable to heat the gas as hot as possible within the trail, but mere heating can also cause ionization and therefore for any gas medium there will be a trade-off between heating the gas to a high level to enhance breakdown length and heating it little enough to avoid excessive ionization. As an example, the absorption length of air is drastically reduced at temperatures in the range of 5,000°K. At this temperature, air exhibits an equilibrium electron density of about 10^{14} per cubic centimeter, which gives a plasma absorption length for 10.6 micron radiation of about 20 meters, as compared with the normal atmospheric absorption length of approximately 10 kilometers.

The high voltage supply used as the discharge source should be sufficient to provide reliable breakdown over the length of the initial low density trail required for a particular application of the invention. A 110 kilovolt source, which was used in the experiment described hereinafter, was adequate for laboratory proof of the principle of the invention, but would of course be considered small as compared with the source required for longer range applications of the invention. The high voltage source has minimal requirements for both its voltage and its energy. If the voltage is too low, the discharge will not take place over the desired trail length, but even if the initial voltage level is sufficient but the source cannot supply sufficient energy, the ionizing potential wave associated with the propagation of the electrical discharge will not travel very far along the beam trail which provides the guidance. This is because the source must deliver sufficient energy to the breakdown streamer tip practical allow it to continue ionizing the air as the tip of the electron-avalanche proceeds along the low density trail. Thus, the voltage and the energy required are both This to, and increase with, the length of the trail to be ionized.

The energy in Joules required to excite a given gas in the trail into ionization can be calculated in advance knowing the density of the molecules and the approximate diameter and length of the laser trail over which the ionizing potential wave is to be discharged. This invention sets forth methods and apparatus for establishing straight highly ionized conductive paths in gas media where the length of the path is referred to sometimes as "relatively long". The "long" path referred to herein is defined as being long with respect to the length of path which could be initiated in the ambient gas by the discharge energy source acting alone. The disclosure also defines a gas density ratio, i.e. the final density divided by the initial density of the gas, which will suffice to guide an ionizing potential wave and enhance its range. This density ratio varies from about one-tenth to about nine-tenths, since at about one-tenth the temperature of most gases in the trail is becoming so high that excessive thermal ionization is taking place; whereas at nine-tenths the gas density difference is becoming too small for pratical utility. The distance traversed by an ionizing potential wave from the high-voltage generator can be improved by superim-

posing an A.C. ripple on top of the high-voltage source pulse. THis can be done either by adding L-C components in the generator itself to make it ring at a frequency which is high enough to place plural A.C. cycles on top of the generator's D.C. pulse, for instance, at 250 kilocycles, or alternatively by adding an oscillator or a driven L-C circuit through which the generator's pulse is applied to the ionization trail, the resonant frequency of the added circuitry being such as to provide plural cycles of an alternating component on top of the high-voltage source pulse, for instance again, at 250 kilocycles so as to provide 20 or more cycles superimposed upon the 50 microsecond pulse of the Marx generator.

The techniques described in this disclosure may of course be used in other gases than air, and at other gas densities than atmospheric density. The detailed atomic and molecular structure of each of the various gases or mixtures governs the interaction of laser beams with them, because such properties as energy levels, collision cross-section, multi-photon absorption efficiences, and excited-state lifetimes combine to determine the effectiveness of a given laser beam for producing trails in a given medium. The equations and discussions hereinafter given are sufficient to indicate the relationships between the properties of the gas medium including its pressure, temperature, specific heat ratio, thermal conductivity, and absorption length; and the properties of the laser including its frequency, pulse length, and power density. For a particular practical application certain of these variables will be fixed, and the remaining variables can then be adjusted to obtain the desired result. It is obvious that if the initial selection of variables is too restrictive, then the desired result is precluded. There are just certain ranges of parameters within which this technique can be made to work.

The present invention is useful for many different applications, in providing a highly conductive transmission path capable of conducting either intelligence or power. Such a transmission path can be used to complete a circuit using the earth as a return path, or two such transmission paths can be established between stations for the purpose of "two-wire" transmissions therebetween. Moreover, a highly conductive single path established by the present invention can be used to discharge clouds, to discharge aircraft or missiles approaching or leaving the earth and having undesirable electrostatic charges on them, or to establish in the air an antenna monopole. In the latter case the initial heated low density gas trail is extended into the atmosphere by the laser and then the high-voltage source is used to ionize the low density trail to a useful level of conductivity for an antenna radiating element. The high-voltage source can provide a pulse coupled between the ground and the base of the laser beam, such a source being provided with sufficient energy capability to propagate the pulse in the form of an ionizing potential wave which travels up the initial low density trail to a height which is determined by the number of Joules which the high-voltage source can deliver. Undoubtedly many other uses for the highly ionized path established by the present invention will occur to persons skilled in the art.

Other objects and advantages of this invention will become apparent during the course of the following discussion of several practical configurations of the invention as shown in the following drawings, wherein:

FIGS. 1A, 1B and 1C comprise three related experimental showings in which electrical discharges were respectively unguided, partially guided, and fully guided between electrodes in gas media;

FIG. 2 is a drawing of an initial preferential path of reduced gas density laid down by a laser beam passing through a gas medium;

FIG. 3 is a diagram showing schematically the manner in which an ionization potential wave is propagated along a low density trail laid down by a laser, the ionizing potential wave having a tip at which electron avalanching occurs to propagate the wave along the laser trail;

FIG. 4 is a schematic diagram of a system according to the invention showing a laser establishing a low density trail in a gas medium, and a high-voltage discharge source discharging through the trail;

FIG. 5 is a diagram of a modified form of the invention in which a high powered source is discharged through a gas medium into a remote load using two lasers, each coupled to the discharge source and their beams intersecting in such a way as to include an electrical load so that the two laser beams, the power source, and the load are all in series;

FIG. 6 is a further modified embodiment of the invention showing a laser beam passing through a gas medium, such as air, to form a vertical monopole trail in which the gas density is reduced and showing a pulsed high power source applied near the lower end of the trail to make it conductive by propagating an ionization potential wave upwardly along the laser trail;

FIG. 7 shows a system similar to FIG. 4, but wherein a component of alternating ripple is applied on top of the high-voltage supply potential before applying the high voltage supply to the low density trail laid down in a gas medium by the laser beam;

FIG. 8 shows concentric laser beams in which a first laser lays down an in-close low density trail, and a second laser of different characteristics has its beam pass through this low density trail, which was made more transparent by the first laser, and heat the gas beyond it to provide a continuing low-density trail extending beyond the one heated by the first laser; and

FIG. 9 shows a concentric-beam system functionally similar to that shown in FIG. 8, but wherein the lasers are co-axial.

Referring now to FIG. 1, this figure illustrates in three adjacent and related views, 1A, 1B and 1C a laboratory-type demonstration showing the creation in dense gas media of preferential low-density trails which can be used to effectively channel or guide a high voltage electrical discharge between electrodes spaced too far apart for the discharge to occur in the absence of the initial laser trail.

FIGS. 1A, 1B, and 1C are all similar to the extent that they show three electrodes M1, M2, and M3 located within a transparent container C in which a gas G is confined, approximately at atmospheric pressure. The difference between these three views of FIG. 1 resides mostly in the gas itself which is within the container C as will be hereinafter explained. Gas particles are schematically shown as dots within the container C. Actually, it is assumed that a gas is present in all figures of all drawings, although it is shown only in some of the figures for the sake of simplicity. The electrode M1 is

connected to one side of a high voltage power supply S, whereas the electrodes M2 and M3 are both connected to the oppsoite side of the poser supply, and the only difference between the paths from electrode M1 to M2, or from the electrode M1 to M3, is the path length and the fact that a laser beam B is passed through the path between M1 and M3.

As mentioned above, in order to provide a lengthened preferential discharge path for the high voltage supply S, it is necessary to increase the temperature of the air in the path B by dissipating energy from the laser into that path. In this particular demonstration, a CO_2 laser was used which radiates at a wavelength of 10.6 microns to create a low density trail through the gas G, provided the gas is sufficiently absorptive to radiation at 10.6 microns. The gas contained within the container C in FIG. 1A is air at atmospheric pressure, but it will be recalled from an earlier statement that the absorption length for air with respect to this wavelength of radiation is in the neighborhood of ten kilometers. Therefore, the laser beam shown in FIG. 1A passes directly through the air within the container C and deposits practically no energy in that air because of the fact that the path length, being only a few centimeters, is badly mismatched with respect to the absorption length of air. What is desired is to somehow reduce the absorption length of the air in the container from several kilometers to something in the neighborhood of 50 centimeters or less. The spacing between the electrodes shown in the various views of FIG. 1 is 14 centimeters for the path from the electrode M1 to the electrode M2, and 20.4 centimeters from the electrode M1 to the electrode M3. Because of the fact that the short airpath through which the laser beam B passes in FIG. 1A absorbs very little energy from the beam, the path B between the electrodes M1 and M3 is only very slightly heated, not sufficiently to provide significant guidance. Therefore, the high voltage supply, which is about 110,000 volts, is only sufficient to jump an arc from the electrode M1 to the electrode M2, but is not sufficient to pass a discharge from the electrode M1 to the electrode M3. Accordingly, the discharge D shown in FIG. 1A represents a common unassisted type of discharge between the electrodes M1 and M2 in which the discharge path is not lengthened, and is not straightened. Instead, this discharge tends to meander and wander transversely of a straight line between the electrodes, and thus the guidance and path lengthening which is the object of the present invention is not present in FIG. 1A.

It will be recalled that the spectrographic characteristics of a gas mixture, as discussed above, depend upon which molecular species are present within the gas. Therefore, it is possible to change the absorption length of the air within the container C by adding ammonia gas thereto, which has a drastic effect upon the absorption length because of the fact that ammonia is strongly absorptive at 10.6 microns. Thus, in FIG. 1B enough ammonia has been added to the air so that the gas G2 within the container C in that figure amounts to about 1 percent ammonia. As a result of this change in the gas mixture, the gas now absorbs considerably more of the laser beam energy, so that the path B between the electrodes M1 and M2 now accomplishes partial guidance of the discharge, i.e. sufficient to guide the disharge about one-third of the way from the electrode M1 toward the electrode M3. However, in FIG. 1B the discharge still breaks away from the path and goes to the electrode M2, showing a failure in the guidance. Thus, the discharge is straight and guided over the portion of the discharge labelled D1, but subsequently escapes from the guidance path and follows a wandering path D2 to the electrode M2.

FIG. 1C is similar to the other figures except that it shows a fully guided discharge path D3 which has been achieved between the electrode M1 and M3. In FIG. 1C the ammonia content in the gas G3 has been raised to approximately 10 percent, and at this percentage the absorption length of the gas mixture is reduced to about 50 centimeters. The laser beam is present at about 75 watts for 0.3 seconds and deposits about 11 Joules of energy into the gas mixture to form the initial low density trail which succeeds in guiding the discharge D3 to an electrode M3 which is located further away than the electrode M2. As a result, the discharge path is increased in length by about 40 percent and the ionization path is made substantially perfectly straight. This guidance is achieved by reduction in density of the gas in the discharge path by heat absorbed from the laser beam, the reduction in density being to about 34 percent of the density of the ambient gas mixture in the remainder of the container C. An external control circuit A is used to control both the laser beam and the voltage discharge from the high-voltage source S.

With proper "matching" of the absorption length of the gas to the approximate discharge length desired, three things are accomplished using the laser beam to create an initial heated trail, namely, the discharge from the particular high-voltage source available is accomplished between electrodes that are spaced further apart than the normal breakdown length for that voltagea at the ambient gas pressure; the discharge path is made straight through the gas between the electrodes without a tendency to wander; and the time required for the high voltage to travel the gap between the electrodes is decreased by increasing the velocity and the straightness of the discharge.

There are two cases of laser-produced thermal channels to consider. First, consider heating the trail by a pulse of duration time much shorter than the thermal expansion time of the cylindrical trail through the gas which is heated by the laser beam as shown in FIG. 2. In the following discussion the subscript o refers to ambient unheated conditions, the subscript 1 denotes initial heat effected conditions, and the subscript 2 denotes conditions after the heated gas has had time to expand from its initially-heated condition. The pulse beam heats an initial cylinder of gas of radius r_1 to a Kelvin temperature T_1 which is greater than T_o, and to a density ρ_o which is initially unchanged. The gas then expands to a state ρ_2, r_2 in the wake of the pulse. Assuming the gas expands adiabatically to a final state in pressure equilibrium with the surrounding gas, it follows that

$$(r_2/r_1)^2 = (T_2/T_o) = (\rho_o/\rho_2) = (T_1/T_o)^{1/\gamma}_{Pulse} \quad (1)$$

where γ represents the specific heat ratio. The radiation energy absorbed per centimeter at a distance x from the laser is $E\ exp(-x/L_{ao})\ L^{-1}_{ao}$, where E is the pulse energy in Joules and L_{ao} is its absorption length. The quantity T_1/T_o required in (1) is thus

$$(T_1/T_o)_{Pulse} = 1 + [10^7 E\ exp(-x/L_{ao})/\pi\ r^2_1\ L_{ao}\ c_v\ \rho_o\ T_o \quad (2)$$

where c_v is the specific heat of the gas at constant volume. In air at atmospheric pressure $\gamma \cong 1.4$, $c_v = 7\times10^6$ erg/gm/deg, and for $x < L_{ao}$ equation (2) gives $(\rho_o/\rho_2) \cong (1 + 1.3\ E/r_1^2\ L_{ao})^{-.71}$ where E is in Joules, r_1 and L_{ao} in cm, and $T_o \cong 300°K$.

Next consider the case in which a CW laser is used so that the heated gas channel evolves more gradually through a series of constant pressure states. As heating proceeds, gas pushes out beyond the beam radius r_1 with radial velocity V. From the constant-pressure energy and mass conservation equations we find $V = r_1 V_1/r$ in the region $r > r_1$. Now the temperature of gas inside the (W beam, of total power $\dot{E}$, increases according to

$$\rho_1 c_p\ dT_1/dt = \dot{E}\ exp(-x/L_a)/\pi\ r_1^2\ L_a \quad (3)$$

where we assumed ρ_1 and T_1 to be spatially uniform for $r < r_1$, and L_a is the absorption length for density ρ_1, i.e. $L_a = L_{ao}\ (\rho_o/\rho_1)$. For the region $x < L_a$ this integrates to

$$(T_1/T_o)_{CW} = (\rho_o/\rho_1)_{CW} = 1 + [E(t)/\pi\ r_1^2\ L_{ao}\ c_p\rho_o\ T_o \quad (4)$$

where $E(t)$ is the total laser energy emitted in a certain time t. Next, equating the gas flux expanding out of the beam $(2\pi\ r_1\ \rho_1\ V_1)$ to $-\pi r^2_1(d\rho_1/dt)$ and noting $\rho_1 T_1 = \rho_o T_o$, this gives $V_1 = (r_1/2T_1)dI_1/dt$. The outer edge of the expanding cylinder thus reaches a radius r_2 which follows from $\dot{r}_2 = r_1 V_1/r_2$ as

$$(r_2/r_1)_{CW} = [1 + 1n\ (T_1/T_o)\ ]^{one\text{-}half} \quad (5)$$

The above derivation of equations (4) and (5) neglects thermal conduction, but it is estimated that thermal conduction, can be neglected only if $(K \cdot t/\ \rho_1 c_p)^{one\text{-}half} << r_2$. In the CW heating case the gas refractive index n will also play a role. If $n > 1$ the beam tends to diverge, but for $n < 1$ the rarefaction channel would tend to confine the beam.

Still referring to FIG. **2**, this figure illustrates a low density trail comprising a thermal rarefaction channel which has a lifetime determined by thermal conduction, as follows:

$$t_c \cong r_2^2\ c_p\rho_2/2K \quad (6)$$

where K, c_p and ρ_2, are respectively the thermal conductivity, specific heat at constant pressure, and density in the cylinder of radius r_2. For example, in air at atmospheric pressure $\rho_o \cong 1.2 \times 10^{-3}$ gm/cm^3, $c_p = 10^7$ erg/gm/deg, and $K = 2.5 \times 10^3$ erg/cm/deg. Choosing $r_2 = .5$ cm and $\rho_2 \cong 0.6 \times 10^{-3}$ gives $t_c \cong 0.3$ sec.

The above thermally guided discharge mechanism is distinct from the one discussed in copending application, Ser. No. 27,369 to Vaill, in which a laser-produced ionization trail provided the preferred breakdown path. In that case the ionized trail decays within a few microseconds, except in high density plasma "bead" regions of gas breakdown where thermal cooling controls the decay time of the electron density, the lifetime being so short that difficulty occurs in channeling long distance discharges.

One practical use to which the above formulas can be put is to explore the possibility that a lightening discharge could be triggered and perhaps guided by a laser-produced rarefaction channel. Just prior to initiation of a lightening step-leader the electric field intensity beneath a cloud approaches the air breakdown value. Either (2) or (4) shows that a channel of length approximating L_{ao} cm, radius r_1 cm, and density $\cong .5\ \rho_o$ can be created in such a region with a total energy

$$E \cong r^2_1\ L_{ao}\ \text{Joules} \quad (7)$$

Although large energies are most readily obtained using a CW laser, the above energy must be delivered in a time less than 10^{-3} r_1 second. Otherwise winds, of say 36 kn/hr, would convect unheated air through the beam within the heating time.

Another constraint involves the beam divergence. Suppose a laser of radius R_L and beam divergence $\delta\theta = 2\ \lambda\ /R_L$ (twice-diffraction limited, is focussed down to a beam of radius r_1 and length $\sim f$. The minimum attainable value for r_1 is $\sim f(2\ \lambda\ /R_L)$. For example, if $\lambda = 10.6\mu$, $R_L = 50$ cm, $f = 0.5$ km, we find $r_{1Min} \cong 1$ cm. In this case, due to the long absorption length of CO_2 radiation ($L_{ao} \sim 10$ km), (7) leads to an energy requirement of $\sim 4.10^6$ J. However, this figure drops rapidly as L_{ao} and λ decrease. For a hypothetical laser with $L_{ao} =$ 1 km. and $\lambda \sim 5\ \mu$, the energy requirement would be 10^5 Joules.

FIG. **3** is a diagram illustrating the manner in which a high voltage ionizing potential wave, i.e. an electrical breakdown streamer, propagates along a low density rarefaction trail laid down by a laser. This trail of radius r_2 is labelled **10** in FIG. **3**, and the high voltage streamer which is propagating to the right at velocity V is labelled **11** and has a field terminating in a tip **12.** At the tip **12** electron avalanching continuously takes place to propagate the potential wave along the trail, as long as the energy of the high voltage source creating the ionizing potential wave is great enough to sustain it despite the loss of energy being dissipated at the tip to ionize the gas molecules G5 located within the low density rarefaction trail portion **10.** Assuming that most of these gas molecules become ionized, the resulting path **11** will comprise a plasma which is highly conductive and which is progressing not only rightwardly along the rarefaction trail **10,** but also has a tendency to expand radially. Fortunately the longitudinal progress of the tip **12** is musch more rapid than the radial expansion of the plasma path, and therefore, the path remains fairly well defined for a useable interval of time. However, if the high voltage discharge source maintains a high energy input into the plasma path **11,** it will eventually begin to wander in radial directions and will tend to expand unevenly, which is undesirable in a system where straightline propagation of the path is an object. It is important that the degree of rarefaction of the trail initially laid down by the laser and labelled **10** be adequate to keep the tip **12** running along it, rather than striking out in a direction of its own selection as shown in FIG. 1B. In general, the higher the potential of the ionizing wave **12,** the more distinct the initial trail must be in order to successfully guide the tip.

Going back again to the particular example shown in FIGS. 1A, 1B, and 1C, the final ionization in the high voltage discharge path D is assumed to be substantially complete and reaches approximately 10^{19} ions per cc. However, the present invention is not to be limited to this virtually-complete degree of ionization in view of the fact that lower degrees of ionization may be useful depending on the particular purpose which the invention seeks to accomplish in a practical configuration. When forming a low density trail through a particular gas, it is believed that the energy which must be deposited to form an initial guidance trail by the laser should be in a range from about 20 percent to about 800 percent of the initial ambient energy of the gas. For in-

stance, air at room temperature has an energy content of approximately 1/10th of a Joule per cubic centimeter, so that it is desirable to add energy in the range of from 0.02 Joules per cubic centimeter up to about 0.8 Joules per cubic centimeter when forming the initial low density guidance trail. This energy is initiated in the form of the laser beam and is transferred to the gas as a thermal increase, which causes the gas to expand and temporarily produce a high temperature low density trail. Where pulsed radiation is used to lay down the initial thermal trail for guidance purposes, the duration of the pulse is assumed to be much shorter than the cooling time of the gas in the trail, meaning that the pulse must be able to put energy into the trail faster than the energy is dissipated therefrom. However, there is such a thing as having the pulse duration too short, such as would involve an excessive peak power, which would cause a prohibitive degree of ionization in the trail, thereby making an initial portion of the trail opaque to the laser beam. Conversely if the pulse duration is too long and the peak power is proportionately lower, the laser trail can wander and cool itself by dissipation of the heated gas due to convective buoyant forces, or even windage. Therefore, the pulse duration of the laser should be shorter than the characteristic time for wandering of the heated trail due to buoyancy and windage forces. Where the rarefaction trail is horizontal the convective forces are much more damaging to the lifetime of the heated trail through the gas, than is the case where the heated trail is vertical. In the latter case the duration of the trail lifetime can be as great as one second in still air. In any event, the pulse power level should be below the level at which the gas is heated to a temperature causing ionization.

Going back to a consideration of equation (4), for example, if an experiment were conducted resembling the one described in connection with FIG. **1** using a CW laser, where E is 21 Joules, r is 0.75 centimeters; and L_{no} is 40 centimeters, when these values are substituted in equation (4) where the distance of the discharge through the absorbing gas is also equal to 40 centimeters, then the ratio of the rarified heated trail density to the ambient gas density comes out to about 0.59. As mentioned above, the Paschen breakdown curve is linear for breakdown voltages versus gas density relationships at about one atmosphere, and remains linear down to about 0.005 atmosphere for all intents and purposes. Thus, from this Paschen curve it can be seen that a range enhancement of about 1.7 times the initial breakdown range will be obtained for this degree of rarefaction of the gas in the initial trail. The measured values by actual experiment similar to the one just hypothicated were 21.6 centimeters using the laser beam and 12.7 centimeters without laser enhancement, thus giving a discharge enhancement of about 1.7, which agrees with the calculated value.

Referring now to FIG. **4**, this figure shows an embodiment including a laser **20** passing a beam **24** through a focusing lens **21** and through two electrodes in the form of sleeves **22** and **23.** The laser **20** is selected such that the wavelength of its beam is matched well enough to the length of the trail between the electrodes and to the absorption length of the gas medium G4 that the trail between the electrodes is well heated to provide rarefaction of its density. In subsequent views of the drawings, the gas medium G will not be repeated, but is assumed to be present and to have a mixture selected as discussed above to provide optimum absorption. The system also includes a high voltage discharge source **25** having a large potential difference between its output leads **26** and **27** which are connected respectively to the electrodes **22** and **23.** The high voltage source, as well as the laser, are controlled by a suitable control circuit **28** so as to cause the source to apply its voltage between the electrodes **22** and **23** at a time when the laser beam **24** has deposited most of its energy between those electrodes. In the event that the laser **20** and the source **25** provide outputs which are continuous, as distinguished from pulsed, the control circuit will comprise merely on-off means, but where pulsed lasers and/or pulsed source means are used, the control circuit **28** will deliver separate sequential trigger signals suitable for firing the laser and then firing the discharge source, and also for controlling the rate at which the laser **20** and the source **25** repeat their outputs. As pointed out previously in the present specification, pulsed systems have the advantage of providing quiescent intervals between their output pulses during which the ionized plasma in the portion **24** of the beam which is located between the electrodes can die out to permit the system to start all over again and re-establish a straight-line highly conductive path of narrow and well defined proportions. As was mentioned in connection with the discussion of FIG. **3**, the high voltage plasma streamer continues to expand radially as well as longitudinally along the trail established by the laser so that eventually the resulting plasma will expand to provide a trail of poorly defined radial extent if it is not periodically extinguished by the control circuit **28.**

Referring now to FIG. **5**, this figure shows two lasers **30** and **31** each delivering a beam trail, **32** and **33** respectively, through suitable optical focusing means **34** and **35.** The beams **32** and **33** also pass through electrode coupling means **36** and **37.** The beam from each laser is focused to intersect upon a load L which can be remote from the lasers **31** and **32,** which lasers may be directed by mechanical tracking means so as to maintain their beam always impinging upon the load. A high voltage discharge source **38** is connected at its output so as to deliver a high energy discharge across the electrodes **36** and **37,** and thereby place the source in series with the beams **32** and **33,** through the load L. A suitable control means **39** serves to control the firing of the two lasers **30** and **31** and then to trigger the high energy source **38** across the load through the beams **32** and **33** at a time when the latter have heated their trails to a maximum degree, thereby fully establishing the desired low density in the heated gas. In a pulsed-beam pulsed-source system, the control **39** comprises a trigger circuit for controlling the synchronization between the lasers and the source. The application of the high powered output from the discharge source across the load L results not only in the ionization to a high degree of the gas in the vicinity of the beams **32** and **33** extending from the coupling electrodes **36** and **37** to the load, but also places the power source **38** across the load, either for constructive or for destructive purposes. In the former case, the system becomes a power transmission system, perhaps serving an inaccessible station; whereas in the latter case it could serve as a hole drilling system or as a destructive weapon, for example.

FIG. **5** shows the beams **32** and **33** intersecting at an acute angle above the load L, but it is to be understood that the beams may be made colinear by aiming the two

lasers directly at each other, therby forming one straight trail of extended total length.

Referring to FIG. 6 a system is shown in which a laser 40 delivers a beam through a suitable focusing lens 42 and through a coupling electrode 43. This beam can be directed into the air from the ground, for instance, for the purpose of providing a monopole radiating antenna whose radiator extends to the height of the initially heated laser trail, and is then ionized by the discharge source 44 to that height to provide a highly conductive monopole 45. In a pulsed system, the laser is selected to provide the required wavelength so that the energy of its beam will be dissipated in the gas over the required height of the monopole radiator to guide the high voltage streamer tip from the discharge source 44 to the desired point in space before the streamer tip stops propagating. The pulse is then applied between ground and a point on the beam 41, this high voltage pulse being supplied at a power level such that it will sustain the monopole radiator long enough to have signal intelligence from a transmitter 46 coupled thereto for radiation. The trigger control 47 controls both the laser 40 and the high voltage pulse source 44, and indeed may also control the transmitter 46 so that its transmissions occur only when the highly conductive monopole has been erected in the air and is ready to broadcast the signal intelligence applied to it by the transmitter 46.

FIG. 7 shows an embodiment similar to FIG. 1 and including a laser 50 delivering a beam 54 through suitable focusing lens means 51 and between two spaced electrodes 52 and 53. A high voltage discharge source 55 is coupled by a wire 56 to one electrode, and has its other high voltage lead coupled to the other electrode by way of a high-amplitude AC ripple source 59. A control circuit 58 controls the laser and the supply in the same manner as discussed in connection with FIG. 1. The high amplitude AC ripple circuit 59 comprises a simple LC circuit which responds to the shock of the pulse from the high voltage power supply 55 to provide a ripple component in series with the power supply voltage and at the ringing frequency of the ripple circuit 59, which is high enough to provide at least a few alternating cycles on the top of the unidirectional pulse from the high voltage supply 55. The presence of the AC ripple on top of the high voltage pulse from the supply 55 improves the conductivity of the path 54' behind the ionizing potential wave by increasing the Joule heating loss over the streamer path and thereby creating more ionization, and consequently increasing the conductivity of the channel. One suitable type of discharge supply 55 comprises a Marx generator which is of the type that discharges internal storage means to provide the main pulse output of the supply. It is also possible to internally alter such a high voltage supply by adding inductance at appropriate points within the generator, so as to cause internal capacitances to resonate with the added inductance and thereby produce the AC ripple component on top of the discharged pulse from the generator.

FIG. 8 shows an embodiment using two lasers operating at different wavelengths in order to lay down a long low density trail, for instance directed straight upwardly through the atmosphere. The beam 61 of the laser 60 is directed upwardly by the surface of a partial mirror 62 whereas the beam of the other laser 63 is passed through the partial mirror 62 so that the beam 61 and the beam 64 are combined as shown at 61' to form a vertical composite beam, in the present illustration. This embodiment is useful, for example, to establish a very long low-density laser trail to discharge a cloud on which a high potential with respect to ground has built up, the cloud acting as the discharge source in this case. By operating lasers having two different wavelengths along the same atmospheric trail it is possible to use one of the laser beams to create a low-density trail in the air near the earth and to use the other laser beam to pass through the resulting rarefaction trail, which has thus become more transparent near the earth, and heat the portion of the trail lying beyond the heating range of the first laser and extending from there to the cloud. In other words, the first laser's beam alters the density of the denser portion of the atmosphere near the earth and thus clears a way for the second laser beam to reach out to the less dense portion of the atmosphere near the cloud. These lasers thereby perform their heating functions in series, distance-wise. It is not necessary that it be a cloud which is discharged, for obviously it could be a missile, an aircraft, a helicopter, or some other body. For this purpose the beam is passed through a suitable electrode coupling means 68 which is connected to the ground. If the object to be discharged is not very distant from the laser, then one laser can be sufficient to do the job.

FIG. 9 is similar to FIG. 8, to the extent that it also uses two lasers, operated in the same way to place their effectively heated trails in series distance-wise. In this example,one trail-establishing laser 70 lays down a close-in low-density trail 73 by its beam 71 while the other laser 72 uses its beam 72 to lay down another low-density trail 75 beyond the trail 73. Both beams pass through suitable optical focusing means 70a and 72a and form a composite beam trail which can be used for any useful purpose, for instance, making contact with an object 76. The two lasers 70 and 72 are triggered by suitable control means 77 which may operate them either in the CW or in the pulsed mode. As discussed above, the laser 70 which lays down the close-in low density trail 73 should deliver radiation at a wavelength at which the absorption lenth in the gas medium is rather shorter than the absorption length of that gas for the radiation wavelength of the other laser 72. Other configurations of the two-laser system are of course possible to achieve specific results by superimposing the beams from two different lasers. It should be noted that there are various other beam-combining optical means which can be employed to advantage, depending on the characteristics of the beams.

The following claims are presented covering the novel features of the invention illustrated by the above embodiments, which are not intended to limit the invention.

I claim:

1. The method of establishing in a specific gas medium of substantial ambient density a heated rarefaction trail of reduced density spanning the distance between points across which a high electrical potential is to be discharged and guided in a straight path, including the steps of:

a. selecting laser means having a beam wavelength for which the absorption length in that gas medium is of the same order as the distance between the points across which the discharge is to be guided; and

b. radiating and focusing said beam through said gas medium along said trail with such a radius and with such beam energy that the portion of the energy of the beam which is absorbed in the trail over said distance raises the thermal energy in the gas therewithin by an amount falling substantially within the range of 20 percent to 800 percent but below the level at which substantial ionization of the gas occurs.

2. The method as set forth in claim **1**, including the further step of triggering the discharge of high potential between said points when the heated rarefaction trail has been established in the gas.

3. The method as set forth in claim **1**, wherein the ratio of the gas density ρ_2 in the established rarefaction trail to the ambient gas density ρ_o for a pulsed laser beam lies substantially within the range of 0.1 to 0.9 and is expressed as

$$(\rho_2/\rho_o)_{Pulse} = [1 + (10^7 E\ exp(-x/L_{ao})/\pi\ r^2_1\ L_{ao}\ C_v\ \rho_o\ T_o)]^{-1/\gamma}$$

where r_1 is the radius of the laser beam in centimeters, L_{ao} is the absorption length in centimeters of the gas at the wavelength of the laser, E is the energy in Joules emitted by the laser, x is distance along the beam from its point of origin, γ is the specific heat ratio of the gas, c_v is the specific heat of the gas at constant volume, and T_o is the ambient temperature of the gas.

4. The method as set forth in claim **2**, wherein the discharge of the high voltage is initiated after the laser beam is pulsed on and within the lifetime t_c of the low density trail as determined by thermal conduction, in which

$$t_c = r^2_2\ c_p\ \rho_2/2K$$

where K is the thermal conductivity of the gas, c_p is the specific heat of the gas at constant pressure, r_2 is the radius of the established trail, and ρ_2 is the density of the gas in the trail.

5. The method as set forth in claim **1**, wherein the laser means is pulsed "on" to provide a beam of high peak power and of duration which does not exceed the acoustic transit time of a compressional wave across the radius of the beam as expressed by r_1/V_s, where r_1 is the radius of the laser beam and V_s is the velocity of sound in the heated gas trail, whereby to minimize the tendency of a gas to change its index of refraction and defocus the beam.

6. The method as set forth in claim **1**, wherein the ratio of the density ρ_1 of the gas within the established laser beam trail to the ambient gas density ρ_o for a continuous-wave (CW) laser beam lies substantially within the range of 0.1 to 0.9 and is expressed as

$$(\rho_1/\rho_o)_{CW} = [1 + (E(t)/\pi\ r^2_1\ L_{ao}\ C_p\ \rho_o\ T_o)]^{-1}$$

where r_1 is the radius of the laser beam in centimeters, L_{ao} is the absorption length in centimeters of the gas at the wavelength of the laser, $E(t)$ is the total energy in Joules emitted by the laser in a given time interval, C_p is the specific heat of the gas at constant pressure, and T_o is the ambient temperature of the gas.

7. The method as set forth in claim **1**, wherein as a part of the selecting of said laser beam, the step of doping the gas medium to add it to other components selected to alter its absorption length for radiation at the wavelength of the selected laser for the purpose of adjusting the absorption length of the medium to more closely match the distance between said discharge points.

8. The method as set forth in claim **1**, wherein said laser means selecting step includes the selecting of two lasers of differing absorption wavelengths in said gas medium wherein the first laser has a beam having the shorter absorption length and the second laser has a beam having the longer absorption length; and said radiating and focusing step includes radiating the beams along the same trail such that the first laser beam produces a rarefaction trail extending partially from one point toward the other point and making the gas medium more transparent to the second laser beam, and the second laser beam passes through said more-transparent trail portion and produces a rarefaction trail completing said path to the other point.

9. The method as set forth in claim **1**, wherein said laser means selecting and radiating steps include selecting two lasers, and focusing their beams from different initiating locations to respectively pass through said discharge points and substantially intersect in the vicinity of a third point.

10. Apparatus for establishing a heated rarefaction trail for the purpose of guiding the discharge of high potential electrical energy comprising a path of known discharge distance extending between spaced points through a gas medium of substantial ambient pressure, laser means having a beam wavelength which when passed through said gas medium experiences an absorption length of the same order as said discharge distance, the laser means including means for focusing said beam along said path between said points, the dimensions of the focused beam along the path and the energy of the laser beam which is delivered to the gas medium in the path being adjusted to raise the energy of the medium by an amount falling substantially within the range of 20 percent to 800 percent but below the level at which substantial thermal ionization of the gas takes place, thereby to produce a rarefaction trail along said path between said spaced points.

11. Apparatus as set forth in claim **10**, wherein said spaced points comprise electrodes across which a high potential is connected, and said means for focusing said beam comprises means for directing the beam between two selected electrodes, thereby establishing the discharge therebetween to the exclusion of other paths.

12. Apparatus as set forth in claim **10**, wherein said spaced points comprise electrodes; a source of high potential coupled between said electrodes; and trigger control means coupled to said laser means and to said source and operative to trigger the laser "on" and then to trigger the source "on" to discharge the high-potential through the rarefaction trail when the latter has been established by the laser means.

13. Apparatus as set forth in claim **10**, wherein said supply comprises a pulse discharge direct-current supply with an alternating current ripple superimposed upon the direct-current pulse.

14. Apparatus as set forth in claim **10**, wherein said laser means comprises two lasers having means for focusing their beams to substantially intersect each other in the vicinity of a third point to form a rarefaction trail including said spaced points and said third point; electrodes at said spaced points and intersecting said beams; and a source of high potential coupled between said electrodes.

15. Apparatus as set forth in claim **10**, wherein said laser means comprises two lasers having different wavelengths, including a first laser having a shorter ab-

sorption length in said medium and a second laser having a longer absorption length in said medium, and the lasers including means for focusing their beams along the same trail such that the first laser beam produces a rarefaction trail extending from one point less than all the way toward the other point and making the medium more transparent to the second laser beam; and the second laser passing through said more-transparent trail and producing a rarefaction trail completing said path to the other point.

16. Apparatus as set forth in claim **15,** wherein said two lasers have their focusing means colinearly disposed to radiate along the same path between said spaced points.

17. Apparatus as set forth in claim **10,** wherein said path of known distance comprises an antenna radiation path including an electrode at a lower point therealong and an upper point comprising the top of the antenna radiator, the wavelength of the laser being selected such that the absorption length in the medium substantially equals the length of the radiator; a high-voltage high-energy source coupled between ground and said electrode and having energy limited to propagate a streamer tip along said trail which extends only over the length of the desired radiator; and means operative to discharge the source along the trail while the laser beam is present.

18. Apparatus as set forth in claim **10,** wherein the laser means is pulse operated and has its energy and its time duration proportioned such that said trail energy level will be reached in a time which does not exceed the acoustic transit time of a compressional wave across the radius of the beam.

* * * * *