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April 29, 1969

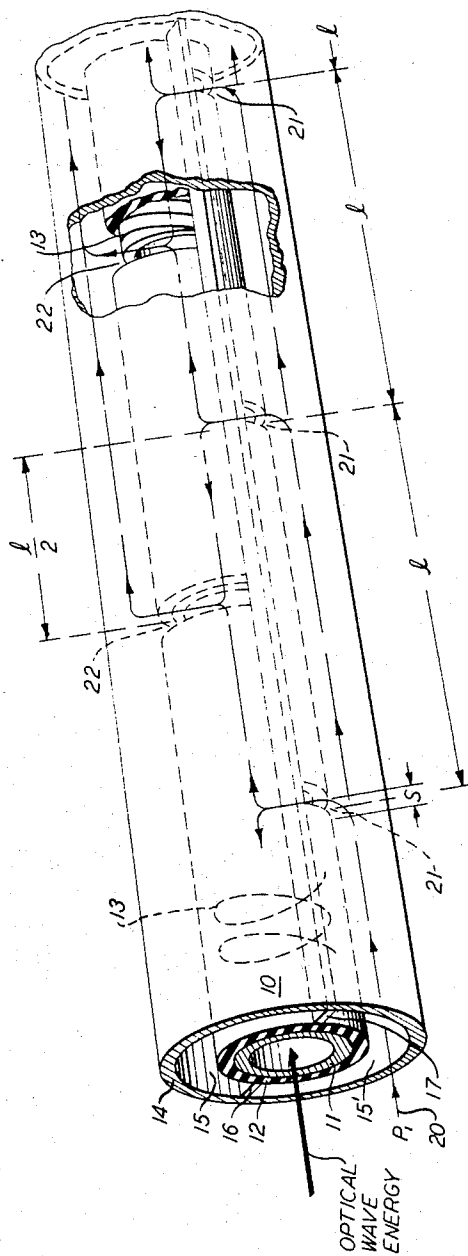
S. E. MILLER
THERMAL GASEOUS WAVEGUIDE WITH GAS-COOLING
COMPARTMENTS LONGITUDINALLY
DISTRIBUTED THEREALONG

3,441,337

Filed July 2, 1965

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FIG. 1



*thermal
gas
waveguide*

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FIG. 2

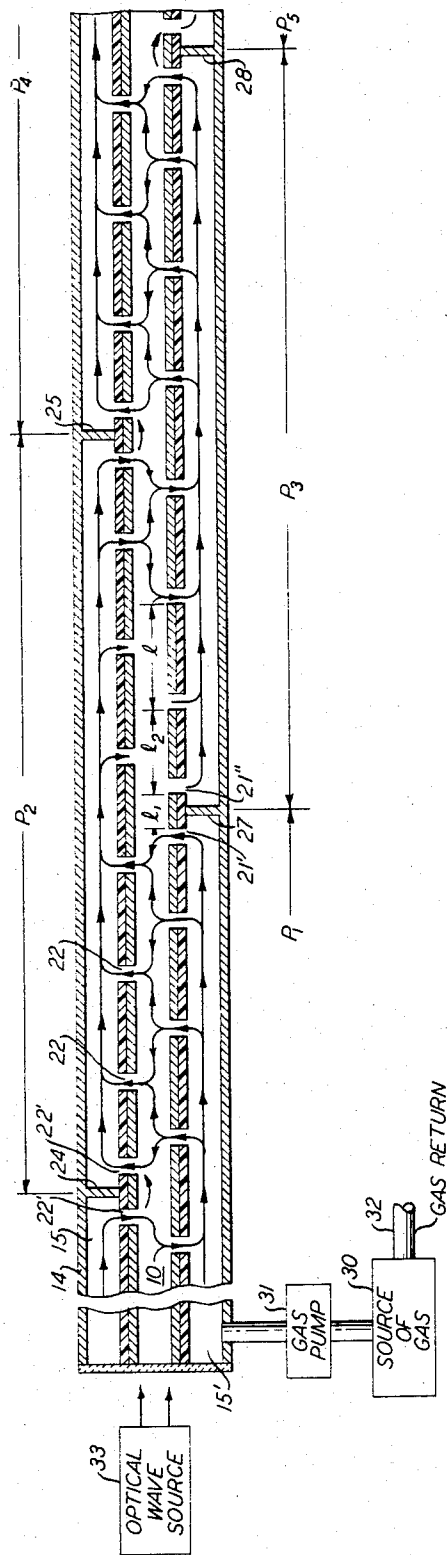
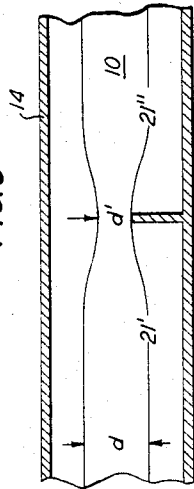


FIG. 3



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THERMAL GASEOUS WAVEGUIDE WITH GAS-COOLING COMPARTMENTS LONGITUDINALLY DISTRIBUTED THEREALONG

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5 Claims

ABSTRACT OF THE DISCLOSURE

A thermal gaseous waveguide comprising a heated inner cylinder through which a beam of electromagnetic wave energy is guided, and a plurality of separate, gas-cooling compartments longitudinally distributed therealong. The compartments are arranged so that a cooled transparent gas is forced out of one compartment, into the inner cylinder where it is heated in a manner to form a radial thermal gradient, and then out of the inner cylinder and into another compartment where it is again cooled. Wave guiding is essentially continuous throughout the system.

This invention relates to thermal gaseous waveguides.

In an article by D. W. Berreman entitled, "A Lens or Light Guide Using Convectively Distorted Thermal Gradients in Gases," published in the July 1964 issue of the Bell System Technical Journal, pp. 1469-1475, there is described a thermal gaseous waveguide particularly adapted for the transmission of optical wave energy. It is a characteristic of the waveguide described by Berreman that a thermal gradient is established across the wavepath as a means of guiding the optical wave energy propagating therealong.

Recognizing that a gaseous waveguide is intended to transmit wave energy over long distances, it becomes apparent that in order for such a system to be commercially attractive, the waveguide advantageously is both inexpensive to fabricate and economical to operate. That is, the structure should be a relatively simple one, and the operating requirements, including the power needed to establish the requisite temperature gradient, the amount of gas used, and the associated equipment needed to maintain the gas flow through the system, should all be as small as possible.

In accordance with the present invention, these preferred features are realized in a waveguiding system in which continuous focusing is accomplished in a hollow, cylindrical warm tube which is insulated from, and surrounded by a parallel duct system which maintains and provides a continuous supply of cool gas.

In a specific embodiment of the invention to be described in greater detail hereinafter, the waveguide comprises a flowing gas contained within a heated cylinder surrounded by an insulating jacket. The waveguide is further surrounded by a coaxial cylinder of substantially larger radius. The region between the waveguide and the surrounding cylinder is longitudinally divided into two equal chambers by means of two heat insulating members which serve both to isolate and to insulate the gas in the two chambers.

In operation, gas from within one of the chambers enters the wavepath through a plurality of semicircular apertures that are longitudinally distributed along one side of the wavepath. The gas flows within the wavepath where it is heated. It is then exhausted into the other chamber through a second plurality of semicircular aper-

tures longitudinally distributed along the other side of the waveguide.

Means are provided for cooling the exhaust gas and for reusing it in the wavepath.

It is a feature of the present invention that the gas is cooled outside of the wavepath, thereby making possible substantially continuous focusing action. In addition, since there is very little "gap" in the lens action, there is materially less restriction on the strength of this focusing action. In spaced lenses, a cut-off is experienced when the lens strength is greater than some prescribed amount. In accordance with the present invention, much stronger lens action can be tolerated before a cut-off is reached, thus permitting bends of greater curvature in the waveguiding system.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is an illustrative embodiment of the invention;

FIG. 2 is a cross-section of the type of waveguiding system shown in FIG. 1, modified to include barriers in the gas chamber; and

FIG. 3 is a modification of the structure of FIG. 2 in which the waveguide diameter at the barrier is reduced.

Referring to the drawings, FIG. 1 shows a portion of a thermal gaseous waveguiding system in accordance with one embodiment of the present invention. More particularly, the system includes a waveguiding section 10 surrounded by a cylinder 14 whose radius is substantially larger than the outside radius of the waveguide.

Waveguiding section 10 comprises an inner circular cylinder 11 surrounded by an outer thermal insulating jacket 12. Advantageously, cylinder 11 is made of a heat conducting material, such as copper or aluminum, as it is the heat derived from cylinder 11 which establishes the requisite thermal gradient in the gas flowing within cylinder 11. Means for heating cylinder 11 are provided in any convenient manner known in the art. For example, cylinder 11 can be made electrically resistive and heated by causing a longitudinal current to flow through the cylinder. Alternatively, cylinder 11 can be surrounded by a separate helical heating element 13, as shown in FIG. 1.

The insulating jacket 12 surrounding cylinder 11 is made of any suitable material, such as one of the presently available plastics (foamed polyurethane or polystyrene) and serves to insulate cylinder 11 from the surrounding regions for reasons which will become readily apparent.

While shown as two separate members for purposes of illustration and explanation, it is understood that cylinders 11 and 12 can just as readily be constructed as a single, unitary element having a substantially uniformly heated inner surface and an insulated outer surface.

The region between the waveguiding section 10 and the surrounding coaxial cylinder 14 is divided into two substantially equal chambers 15 and 15' by means of two thermal insulating slab-like members 16 and 17 which extend longitudinally along the waveguiding structure diametrically opposed to one another. Each member makes contact with the outside surface of jacket 12 along its entire longitudinal length, and extends radially therefrom to the inner surface of the cylinder 14, thereby isolating the two chambers 15 and 15'.

A plurality of apertures 21 and 22, communicating between each of the respective chambers 15' and 15 and the interior of cylinder 11, are longitudinally distributed along opposite sides of cylinder 11.

In operation, cool gas, indicated by arrow 20, is pumped into gas chamber 15' under pressure P_1 . Means for conditioning the gas, pumping it, and regulating its pres-

sure, including such items as filters, compressors, and heating and/or cooling means, all of conventional form, are not shown in FIG. 1. However, such items are normally included in systems of the type contemplated, as is well known to those skilled in the art.

The gas is injected initially into and flows along within chamber 15' and enters the wavepath by way of the plurality of equally spaced apertures 21 (three of which are shown) longitudinally distributed along one side of waveguide 10. For a semicircular aperture, the aperture area A is given by

$$A = \frac{\pi d s}{2} \quad (1)$$

where

d is the inside diameter of cylinder 11, and s is the longitudinal aperture dimension.

The cross-sectional area, W, of the wavepath is given by

$$W = \frac{\pi d^2}{4} \quad (2)$$

To minimize turbulence, at the opening, the aperture area is advantageously made approximately equal to three times the wavepath area. That is

$$\frac{\pi d s}{2} \approx 3 \left(\frac{\pi d^2}{4} \right) \quad (3)$$

or

$$s = \frac{3}{2} d$$

In addition, the apertures can be covered with a screen or other porous material to help preserve laminar flow. The distance l between apertures is preferably equal to at least 10d.

Typically d is about 1/4 of an inch, s is about 3/8 of an inch, the inside diameter of cylinder 14 is approximately 3/4 of an inch, and l is about 12 inches. In this regard, it will be noted that the drawings are not to scale in that certain dimensions have been exaggerated for purposes of illustration.

After entering cylinder 11, the gas divides and different portions flow away from each aperture in opposite directions, as indicated by the flow lines. As it does so, the gas closer to the heated inner surface of cylinder 11 is raised to a higher temperature than the gas closer to the center of cylinder 11. This establishes a radial temperature gradient in the gas and an accompanying gradient in the refractive index of the gas. As explained in a paper by D. Marcuse and S. E. Miller entitled "Analysis of a Tubular Gas Lens," published in the July 1964 issue of the Bell System Technical Journal, pp. 1759-1782, this gradient in the refractive index of the gas acts upon the optical wave energy propagating within cylinder 11 as a positive lens.

As the gas becomes more uniformly heated, it tends to lose its focusing properties. Accordingly, it is exhausted from within cylinder 11 into chamber 15' by means of the plurality of equally spaced apertures 22, longitudinally distributed along the other side of cylinder 11. Apertures 22 are substantially identical in shape and size to apertures 21. However, they are longitudinally displaced relative to apertures 21 by an amount l/2. That is, apertures 22 are located midway between apertures 21 along the opposite side of cylinder 11.

In the embodiment of FIG. 1, the gas passes from chamber 15' through cylinder 11 and into exhaust chamber 15. By maintaining appropriate pressure differentials between the ends of each chamber, flow of the gas in the desired direction is achieved. In this simple arrangement, the gas exchange between chambers 15' and 15 occurs but once, thus, the total volume of gas required to fill the system is supplied from chamber 15'.

While the cross-section of a typical optical waveguide is small, the waveguide for some applications may be very long, requiring a very large volume of gas. For example, if the volume, v, of gas per second, t, required in a section of wavepath between an input gas aperture 21 and an output gas aperture 22 is v/t, then the flow of gas into each aperture is 2v/t. For n apertures, the total volume of gas flow per second is 2nv/t. In a long line, the number of apertures can become very large requiring the movement of an inconveniently large volume of gas. This would require very large pipes and may well make such an arrangement too large to be practical for most applications. To avoid this possibility, the structure is preferably arranged to cause a small, predetermined volume of the gas to flow back and forth across the wavepath between chambers 15 and 15'.

FIG. 2 is a cross-sectional view of an extended section of waveguide, in accordance with the invention, adapted to reduce the volume of gas that must be pumped through the waveguiding system. Using the same identification numerals for corresponding elements, as were used in FIG. 1, FIG. 2 shows the waveguiding section 10, and the two gas chambers 15 and 15' enclosed by outer cylinder 14. In this second embodiment of the invention, each of the gas chambers is divided into a plurality of separate pressure compartments P₁, P₂, P₃ and P₄ of successively lower pressures by means of a multiplicity of equally spaced barriers, of which barriers 24 and 25 in chamber 15, and barriers 27 and 28 in chamber 15', are illustrative. More particularly, the barriers in the two chambers are longitudinally displaced relative to each other such that the barriers in one chamber are located midway between those in the other chamber.

Each of the compartments communicates to the interior of the cylinder 11 through a plurality of substantially equal apertures 21 and 22, longitudinally distributed along waveguide 10.

In the embodiment of FIG. 1, the space between all adjacent apertures is the same and is equal to the distance l. In the embodiment of FIG. 2, however, the aperture arrangement is slightly modified by the addition of an extra aperture at each barrier. In particular, each barrier separates two adjacent apertures in two adjacent pressure chambers.

For example, barrier 27 in chamber 15', separates the last aperture 21' in pressure compartment P₁ and the first aperture 21'' in compartment P₃. The distance l₁ between these apertures is typically equal to about one waveguide diameter. That is, l₁ is approximately equal to d. To accommodate this extra distance and the extra aperture, the distance l₂ between apertures 21' and 22'' and the next adjacent aperture in their respective pressure compartments P₁ and P₃, is less than the normal spacing l by an amount equal to

$$\frac{l_1 + s}{2}$$

Since this distance is small compared to l, it can be reasonably said that, within each of the pressure compartments, the distances between adjacent apertures are substantially equal.

In operation, the gas flows through the wavepath from pressure compartments of higher pressure to pressure compartments of lower pressure. Thus, in the arrangement shown in FIG. 2, the gas enters cylinder 11 from compartment P₁ of chamber 15', flows along the wavepath, and exhausts into compartment P₂ of chamber 15 by way of apertures 22 where it is cooled. Cooling is accomplished by constructing cylinder 14 of a heat conducting material and maintaining it at some specified temperature lower than the temperature of the gas leaving the waveguide. To this end, means (not shown) are provided for maintaining cylinder 14 at this specified temperature. These means can comprise no more than just

burying the waveguide underground, in which case the specified temperature is simply the ambient ground temperature. If large ambient temperature gradients are anticipated, then additional heating or cooling means, suitably regulated, may advantageously be provided to maintain a more constant ambient temperature in any of the many ways known to those skilled in the art. After being cooled in compartment P_2 , the gas again enters upon and passes through the wavepath, exhausting into a compartment P_3 of chamber 15', of still lower pressure, where it is again cooled. This process is repeated with the same gas progressing longitudinally along the waveguiding system as it passes back and forth through cylinder 11 from a compartment of one chamber, to a compartment of lower pressure in the other chamber. The flow of gas through the system is shown by the flow lines in FIG. 2. It should again be noted that the distance l between apertures is typically much larger than the guide diameter d and, hence, the scale of FIG. 2 is greatly distorted. This was made necessary for purposes of illustration and explanation.

FIG. 2 shows a detached section of waveguide 10' intended to represent the section of waveguide 10 at the transmitting end of the system and includes, in block diagram, an optical wave source 33, a source of gas 30 and a gas pump 31 shown feeding gas into chamber 15'. Also shown is a gas return line 32 which can be employed in a closed system in which the gas is to be conserved. Where air, or some other inexpensive gas is used, it may be more economical not to include a gas return.

It will be noted that at each of the barriers there is an arrow indicating a flow of gas across the barrier which bypasses the intended gas flow. Thus, as an example, there is a flow of gas between adjacent apertures 21' and 21'' across barrier 27. This leakage is accepted in preference to having a solid window in the optical wavepath.

The amount of this leakage v_2 can be estimated, and can be expressed as a fraction of the normal gas flow v_1 as

$$\frac{v_2}{v_1} = \frac{2}{n_1} \left(\frac{d_1}{d} \right)^4 \left(\frac{l}{l_1} \right) \quad (5)$$

where

d is the inside diameter of waveguide 10;

d_1 is the inside diameter of waveguide 10 at a barrier;

l is the distance between apertures between barriers;

l_1 is the distance between adjacent apertures at each barrier; and

n_1 is the number of apertures in each chamber between adjacent barriers.

FIG. 3 shows a portion of the waveguiding system at a barrier, modified to reduce the volume of leakage gas. As can be seen from Equation 5, the volume of leakage gas v_2 varies as the fourth power of the diameter d_1 . Accordingly, the leakage gas can be materially reduced by reducing the guide diameter at the barrier. Thus, in FIG. 3, waveguide 10 (represented simply by a line drawing) is shown tapering from its normal diameter d to a smaller diameter d_1 . A reduction in diameter of about 25 percent would be typical.

To minimize gravitational effects, helical vanes can be included in the wavepath in the manner described by D. Marcuse and W. H. Steier in their copending application, Ser. No. 450,121, filed Apr. 22, 1965 and assigned to applicant's assignee.

In the embodiment described herein, the gas chambers 15 and 15' are enclosed by a cylinder 14. However, it should be understood that the cross-sectional geometry of the chambers is a matter of convenience. Thus, the two chambers can be enclosed by a rectangular enclosure or by two separate enclosures of different cross section. Thus, in all cases it is understood that the above-

described arrangements are illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A system for guiding a beam of electromagnetic wave energy by the formation of a radial thermal gradient across a flowing transparent gas, comprising:

a hollow cylinder wherein said beam is guided;

means for heating said cylinder;

a thermal insulating jacket surrounding said cylinder;

a first plurality of gas-cooling chambers longitudinally disposed along one side of said cylinder;

means, comprising a first multiplicity of apertures longitudinally distributed along said one side, for connecting each of said first plurality of chambers to said cylinder;

a second plurality of gas-cooling chambers longitudinally disposed along the opposite side of said cylinder;

means, comprising a second multiplicity of apertures longitudinally distributed along said opposite side, for connecting each of said second plurality of chambers to said cylinder;

the apertures along said one side being longitudinally displaced relative to the apertures along said opposite side;

and means for forcing said gas out of the chambers disposed along each side of said cylinder, through said cylinder and into the chambers disposed along the other side of said cylinder.

2. A system for guiding a beam of electromagnetic wave energy by the formation of a radial thermal gradient across a flowing transparent gas, comprising:

a pair of hollow, coaxial cylinders of different radii; means for heating the inner of said cylinders wherein said beam is guided;

thermal insulating means surrounding said inner cylinder;

means for longitudinally dividing the region between said cylinders into two substantially equal portions;

a plurality of transverse barriers located within each of said portions for dividing each of said portions into a multiplicity of separate gas-cooling pressure compartments;

the barriers in one of said portions being longitudinally displaced midway between the barriers located in the other of said portions;

a plurality of apertures longitudinally distributed along said inner cylinder to permit a flow of gas between said compartments and said inner cylinder;

and pumping means for forcing a flow of said transparent gas between said compartments and through said inner cylinder.

3. The system according to claim 2 including means located at one end of said system for coupling a beam of said wave energy into said inner cylinder for propagation therein.

4. The structure according to claim 2 wherein the cross-sectional area of said inner cylinder is uniform.

5. The structure according to claim 2 wherein the cross-sectional area of said inner cylinder is less at each of said barriers than the cross section in the region between barriers.

References Cited

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JOHN K. CORBIN, *Primary Examiner*.

U.S. Cl. X.R.

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