THINGS THAT GO FASTER THAN LIGHT

Contrary to common opinion, certain physical phenomena move faster than *c* (the speed of light in a vacuum). This speed is a maximum, however, for the transmission of messages, or of mass and energy

by Milton A. Rothman

It is easy to make something travel faster than light. To anyone educated in the 20th century this statement usually comes as something of a shock. Those who know a little about the theory of relativity are apt to protest: "But Einstein proved that nothing can go faster than light." Even many people who really know better find themselves surprised when they come upon one of the several physical phenomena that do propagate faster than the speed of light in a vacuum. So it seems worthwhile to discuss just what can and what cannot travel faster than light, and to find out what Albert Einstein really said.

Let us begin with something as simple as a pair of scissors. If you think about the point where the two blades intersect, you will realize that as the scissors are closed and the blades become more and more nearly parallel, the intersection point moves away from the pivot faster and faster. Eventually, if the scissors are long enough, the velocity of the point must exceed the speed of light.

To be specific, suppose that the blades extend four kilometers past the pivot and that one blade is held fixed while the other is rotated at one revolution per second. If the pivot point is 10 centimeters below the edge of the fixed blade [*see illustration on pages 144 and 145*], then when the point of intersection is about 2.2 kilometers from the pivot, it is traveling at some 300,000 kilometers per second—a little more than the speed of light. From here out the point of intersection will move faster and faster, reaching speeds far greater than that of light.

But this is just a trick, you say. We have not really sent some palpable thing faster than light. We are merely noticing the motion of a geometrical point, a locus of intersection, not a material body. The trick breaks no laws. After all, there are many other ways of performing it. We could, for example, swing the beam of a searchlight across a screen. If the screen is far enough away, the spot where the light hits will move with tremendous velocity. We could move the spot from Mars to Venus in a second, if we had the appropriate apparatus. Similarly, it is possible to move the electron beam in a cathode-ray oscilloscope back and forth so rapidly that the spot on the screen travels faster than light.

In these examples the only objects that actually move are photons and electrons, and they travel along the beams at their usual speed. The appearance of motion across the screen is supplied by our own minds.

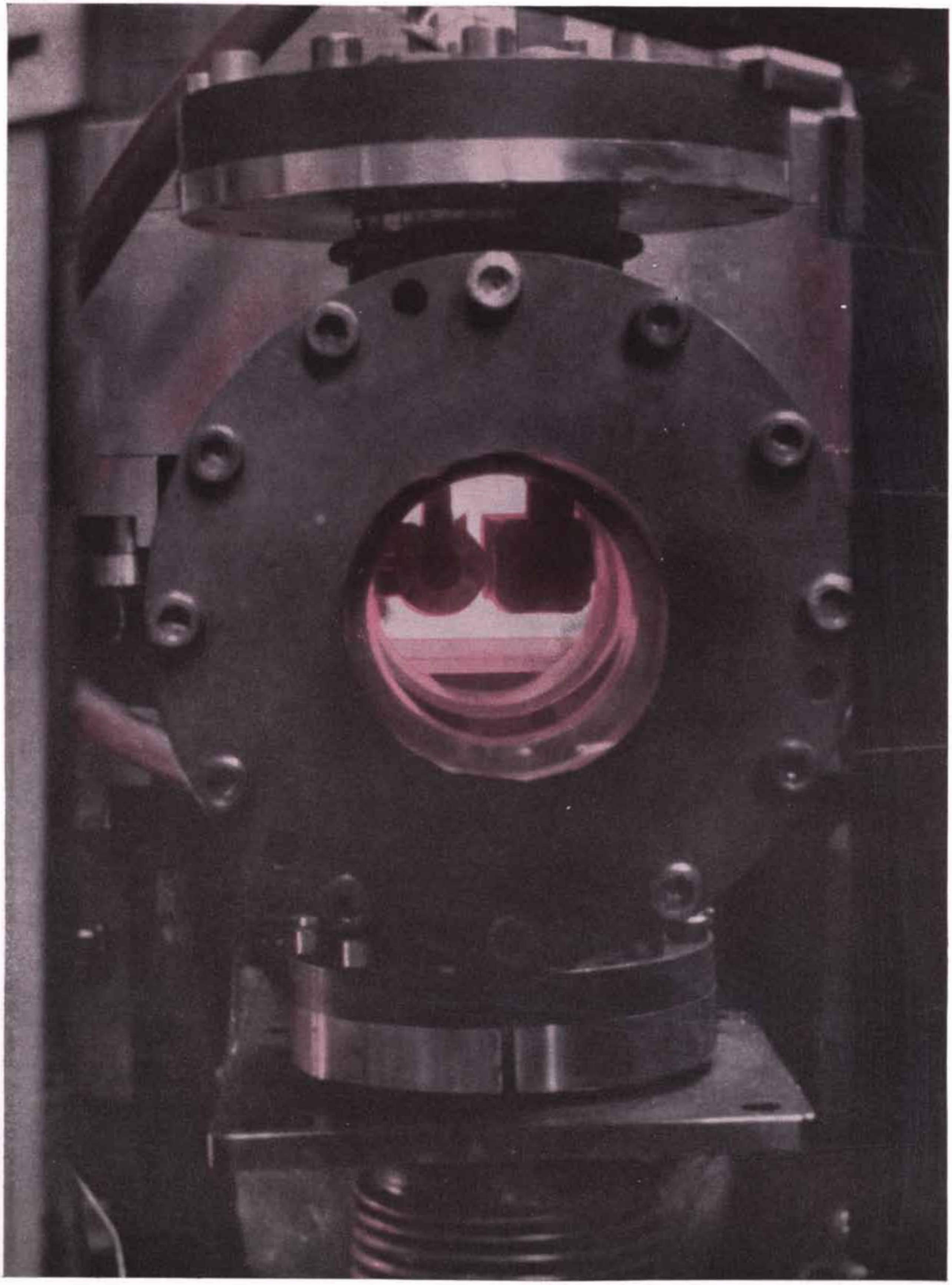
Even granting that the motion is an illusion, something does move faster than light, and we might suppose that we could use it to carry a message. A moment's reflection shows that the searchlight and oscilloscope can be ruled out. Sweeping a light beam from Mars to Venus by means of a projector on the earth is of no help in sending a message from Mars to Venus. However, the scissors seem to offer a possibility. Suppose we gently wiggle the moving arm up and down while it is almost parallel to the fixed arm and thus tap out a code signal. The dots and dashes should then travel out to the far end at a speed faster than that of light.

On closer inspection this superfast telegraph turns out to be based on a false assumption, namely, that the scissor blade is infinitely rigid and that any motion at one end transmits itself throughout the entire length instantaneously. The blade is not rigid, but elastic. When the position of the handle changes, the motion is transmitted along the arm with a velocity that depends upon the arm's elastic properties. In other words, what actually carries the signal is a wave that travels at the speed of sound in this particular blade.

Note that when the arm was rotating at a constant speed, the point of intersection was able to travel faster than light. It was only when we tried to change the motion of the arm that we ran into difficulty. The difficulty is quite general. In order to transmit a message there must be some change of motion. And nature seems to have conspired to make it impossible to send a change faster than light. This is the meaning of the principle of relativity. Einstein never said that nothing could go faster than light. What he said was that no message and no energy (including that contained in the mass of material bodies) could be transmitted faster than light.

The example of the scissors is admittedly farfetched. To find something that really goes faster than light we must look to electromagnetic waves. As a help in visualizing some of their important properties it may be best to talk first about material waves such as water waves.

Imagine you are sitting on a small rock that juts out of an otherwise empty ocean extending in every direction as far as your eye can see. Somewhere over the horizon a huge machine is agitating the water in a regular, rhythmical way and setting up waves. These waves approach you from one side of the horizon, pass by and disappear over the opposite side. We shall suppose that they are ideal waves, with the form of a perfect sine-curve: the crests are all of the same height (that is, the amplitude is constant), and they do not die down as the wave progresses; the spacing between crests does not change



PLASMA, or highly ionized gas, which is producing the rosy glow in this photograph, is a medium in which radio waves have a phase velocity (*see text*) greater than *c* (the speed of light in a vacuum). The plasma is seen through a port in a Stellarator, a device used in thermonuclear research at the James Forrestal Research Center of Princeton University. Dark objects within port are microwave horns, which send waves through the plasma. The increase in velocity is a measure of the density of free electrons.

(the wavelength is constant); the same number of crests passes every second (the frequency is constant).

By keeping your eye on a particular crest and measuring the speed at which it approaches, you can determine the velocity of the wave. What you are actually doing is following the progress of a particular phase in the cycle of vibration of the water particles that make up the wave. Hence the velocity you measure is known as the phase velocity.

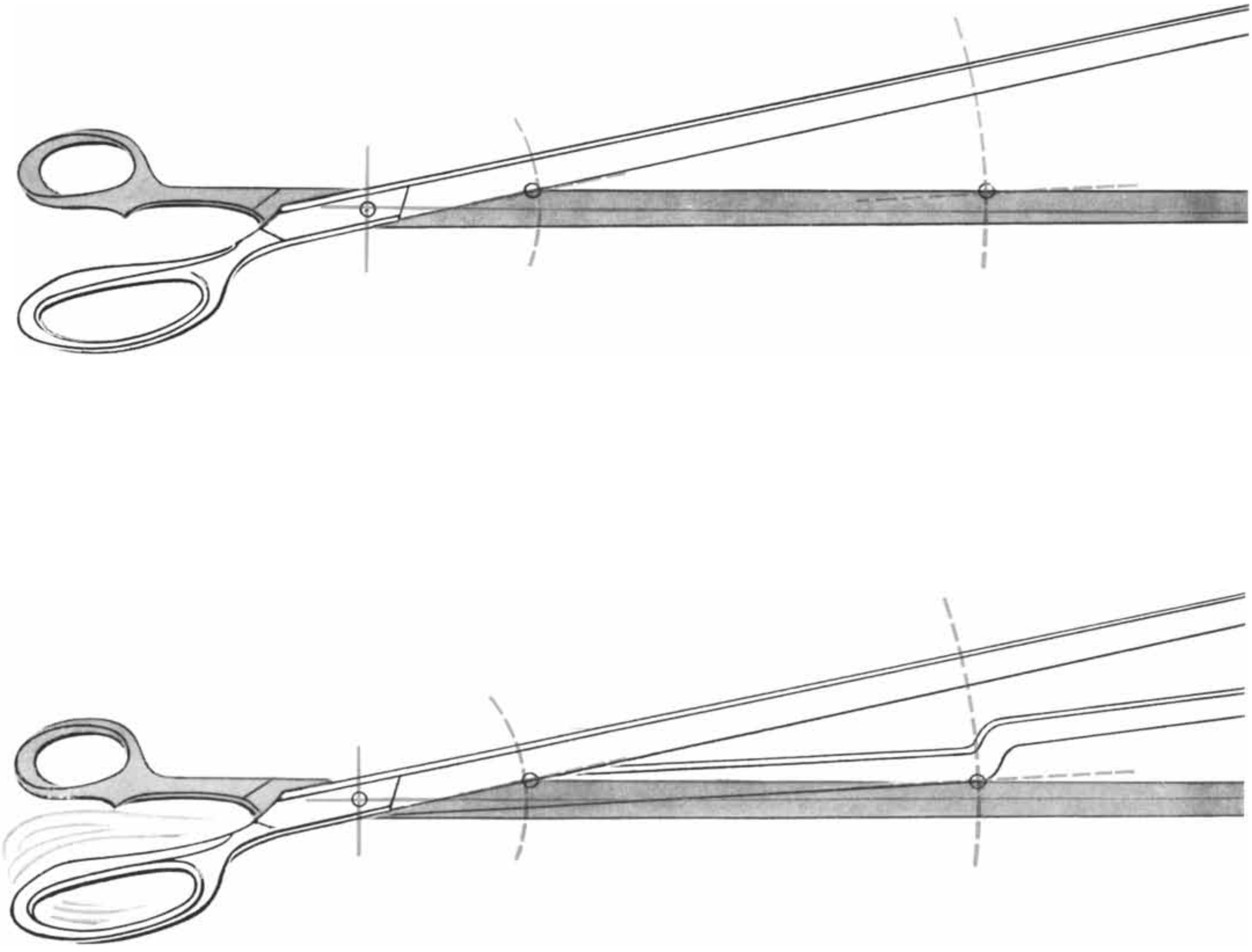
There is another way to find the phase velocity. You can count the number of crests passing in a minute and multiply by the distance between crests. This tells how far the first crest has gone in a minute. In other words, phase velocity equals frequency times wavelength.

What does the wave carry at this velocity? Certainly not a message. The endless, unchanging succession of passing crests can convey no more information than can a still ocean. Nor is energy transmitted. Every point on the surface has exactly the same energy as every other point, and the amount of energy is constant.

Evidently Einstein's restriction should not apply to this wave that carries no message and no energy. In fact it does not; some waves (electromagnetic waves, not water waves) can under certain circumstances have phase velocities greater than the speed of light in a vacuum.

Now consider how a message might be sent by the operator of the water-wave machine to the observer on the rock. Somehow the regular pattern would have to be varied. The variation might take the form of amplitude modulation, for example, where the height of the crests is changed. Another possibility would be to pulse the wave, breaking it up into short, separate packets by alternately starting and stopping the machine.

Whatever stratagem is adopted, it will be found that the significant variations constituting the message progress more slowly than the phase velocity. The pattern of higher and lower crests in the amplitude-modulated wave, or the packets in the pulsed wave, travel



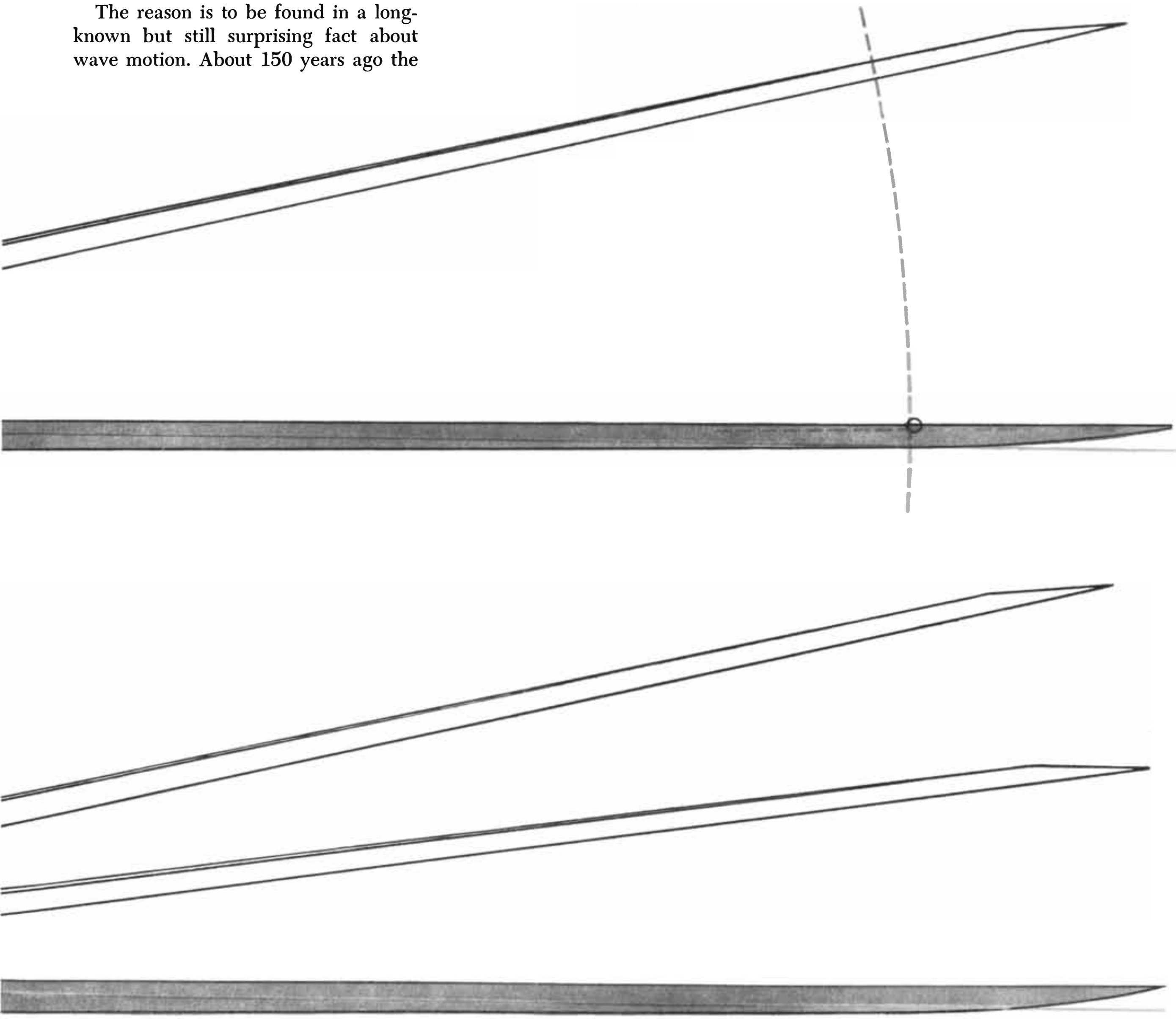
INTERSECTION OF SCISSORS BLADES moves to right at increasing speed as the upper, moving blade rotates at a constant rate. If the blades were long enough, the intersection point could move faster than *c*. In upper drawing the broken straight lines mark the intersection for successive positions of the moving blade after equal angular rotations. In lower drawing the moving blade as a group; their speed is called the group velocity.

For waves in general the group velocity can be less than or equal to the phase velocity, and in a few anomalous cases, greater than the phase velocity. Which rule holds depends on the type of wave and the nature of the medium through which it is traveling. For the large gravity water-waves mentioned above, the group velocity is less than the phase velocity. For small capillary surface waves the reverse is true.

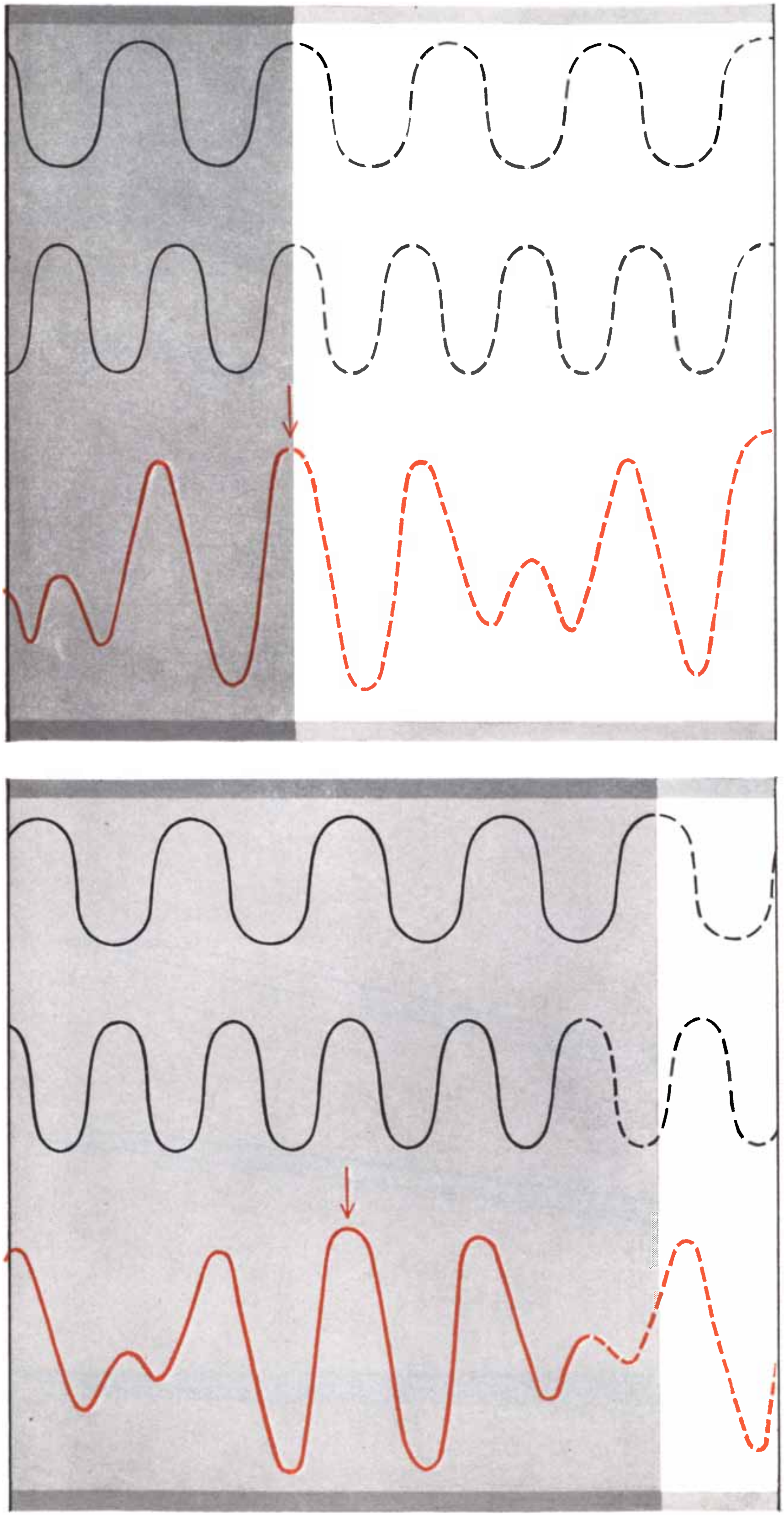
The reason is to be found in a long-known but still surprising fact about wave motion. About 150 years ago the French mathematician Joseph Fourier discovered that every wave group, which means every wave pattern except a perfect sine-wave extending indefinitely in both directions, can be made up by superimposing sine waves of various wavelengths and amplitudes. Not only that, but every wave motion actually contains these pure components; they can be filtered out and detected.

A simple amplitude-modulated signal can be built of just two sine waves [*see illustration on next page*]. Obviously if the two component waves move at the same speed, the pattern obtained by combining them will also travel at that speed. This is the case for light, or for other electromagnetic waves in a vacuum: all the pure sine-waves have the same speed (equal to 299,793 kilometers per second and denoted by c), and the group velocity equals the phase velocity of the component waves.

On the other hand, as a glance at the



is distorted as a result of a sudden closing movement. Now the velocity of the point of intersection depends on the speed at which the jog moves along the blade, and not on the rate at which the handles are pulled together. The progress of the jog depends on the elastic properties of the metal blade, and the motion of the intersection takes place at the speed of sound in the material.



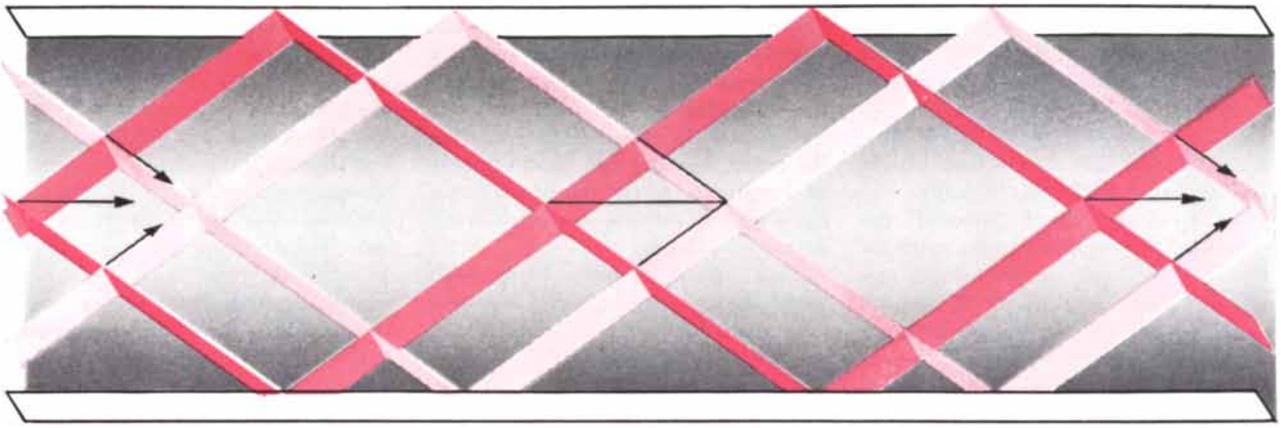
GROUP VELOCITY of a wave form produced by superimposing two sine waves is represented by the advance of the highest crest of the colored curve (*marked with vertical arrow*) from top drawing to bottom one. In the same time interval the upper sine wave, moving at its phase velocity, advanced to point marked by shift of gray area. Lower sine-wave, with a smaller phase velocity, advanced to point at end of solid curve in bottom drawing.

illustration shows, if the component waves move at different speeds, the velocity of the combined wave (the group velocity) is different from that of either component. This is the situation whenever electromagnetic waves travel through a material medium. The velocity of the waves in such media depends on wavelength. Hence different components of a wave have different phase velocities, and in all transparent materials the group velocity is less than any of them.

As a consequence of its change in speed, a light ray passing obliquely from a vacuum to a material medium is bent, or refracted. To check the theoretical relation between velocity and refraction A. A. Michelson in 1885 made accurate measurements of the speed of light in various materials. At first his results seemed to contradict the theory. In carbon disulfide, for example, his velocity measurements yielded an index of refraction of 1.758. But the corresponding figure computed from the observed bending of light rays was 1.635.

The discrepancy was quickly explained when it was realized that the two experiments measured different quantities. The bending of rays depends on phase velocity. Michelson was measuring the speed of short pulses of light; in other words, the group velocity.

In this instance the phase and group velocities, though different from each other, are both less than *c*. Light travels more slowly through carbon disulfide (and other transparent substances) than through a vacuum. But for other portions of the spectrum, such as the far ultraviolet, the phase velocity in a medium is often greater than *c*, as can be demonstrated by refraction. The phenomenon of refraction does not provide a direct measure of speed, but rather of wavelength. When light passes through different media, its wavelength changes, and the amount of bending that takes place at the dividing surface depends on the difference in wavelength. Since the frequency of a wave never changes once it has left its transmitter, and since phase velocity equals frequency times wavelength, the phase velocity varies in the same proportion as the wavelength. But phase velocity itself, in the case of electromagnetic waves, is unmeasurable. We cannot see the crests and follow their progress. When we try to measure velocity directly, we always end up as Michelson did, measuring group velocity. And even where the phase velocity

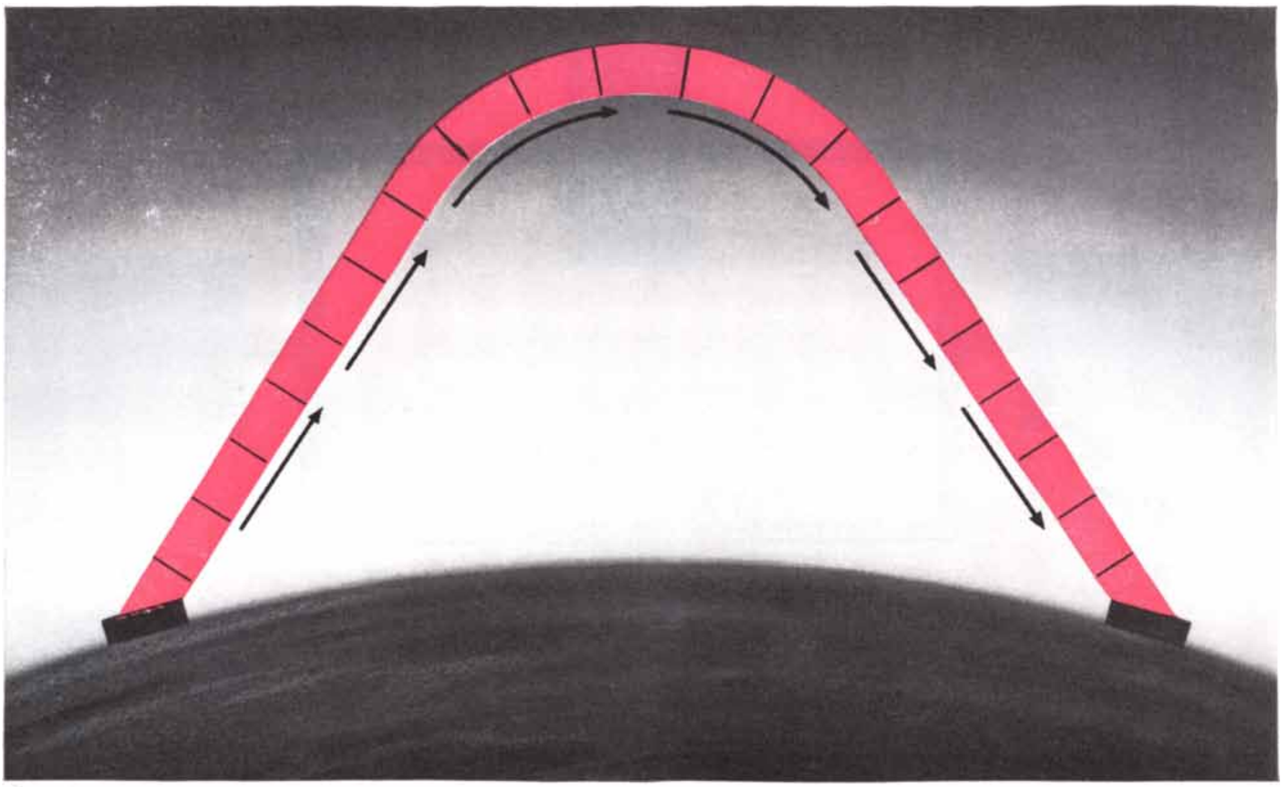


WAVE FRONTS (*colored bands*) **advance through a wave guide by shuttling from wall to wall, in direction of slanted arrows, at speed of light. Point where they cross and reinforce moves faster. Pale bands show a position slightly later than that of dark band.**

is greater than c, nature has conspired to make the group velocity less.

All this would be but a curiosity—a theoretical concept of an unmeasurable quantity—if it were not for certain rather important consequences in the propagation of radio waves. Electrical engineers are familiar with the fact that when very short radio waves, which move through free space at the speed of light, are sent through a long metal pipe, or wave guide, their wavelength grows longer and their velocity increases. The amount of the change varies with frequency in an interesting way. For very high frequencies, where the wavelength is very small compared with the size of the wave guide, the increase is negligible. This is reasonable, because then the wave is practically traveling through free space. As the frequency decreases, however, and the wavelength becomes comparable with the width of the tube, the waves carom off the walls as they advance [*see illustration above*]. As the wave crests shuttle back and forth between the sides, they cross one another, and combine into a new pattern. It is this pattern, the crest of which occurs where the crests of the individual waves add up, that travels straight down the tube.

It is clear from the illustration that



BENDING OF RADIO WAVE (*colored band*) **by ionosphere** (*upper gray area*) **depends on the fact that the phase velocity is increased in the ionosphere. Wave fronts** (*black lines*) **tilt forward as upper parts move faster than lower ones, changing direction.**

the point of reinforcement travels faster than the individual wave-crests, just as the point of intersection of our scissors traveled faster than each blade. Thus we have a wave that travels faster than light, and is longer than it would be in free space for the same frequency.

As the frequency is reduced, the wavelength and velocity in the guide increase until, at a certain critical frequency (determined by the dimensions of the guide), the wavelength becomes infinite and the wave effectively moves with an infinite velocity. This is called the cutoff frequency, for if we try to pass a wave of a lower frequency through the wave guide, we discover that it will not go. The pipe is actually opaque to the radiation.

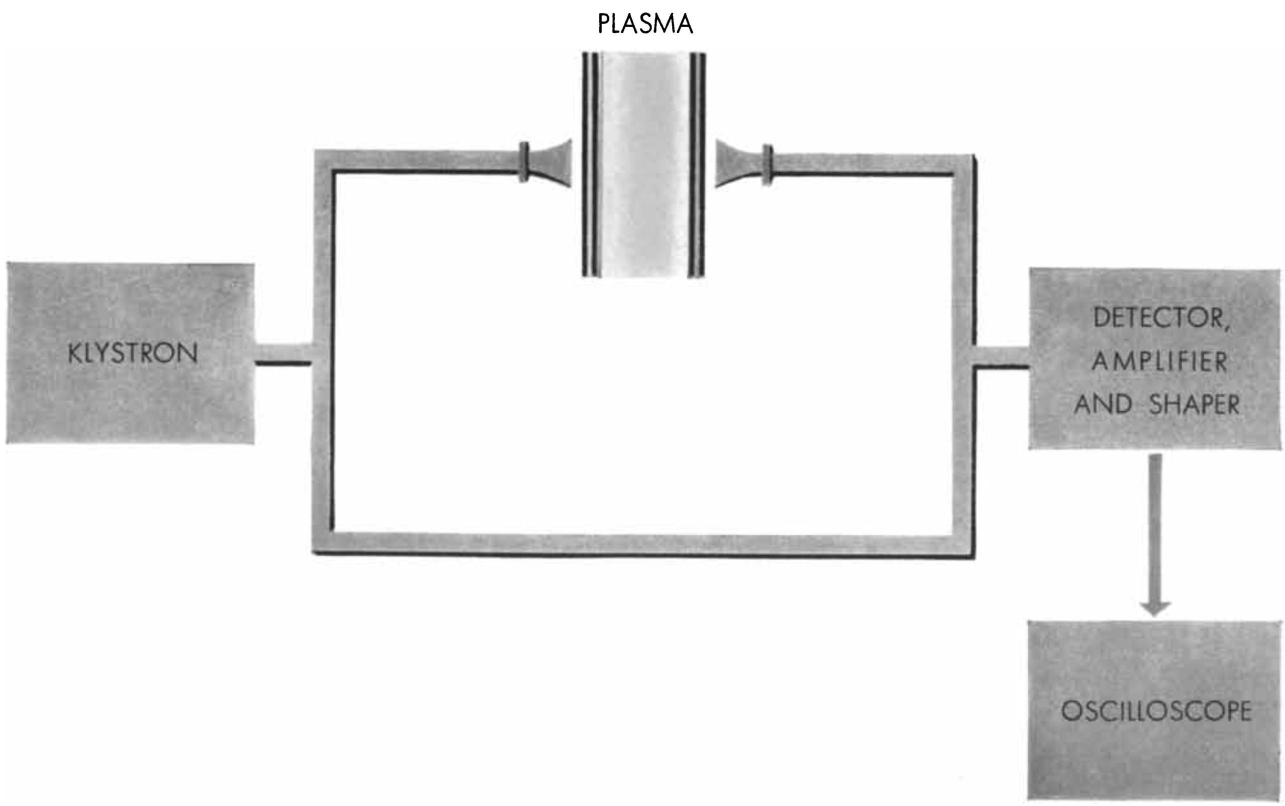
As before, a phase velocity greater than c is nothing to get excited about. The only thing that is moving is an interference pattern between waves. When we start a wave on its way, the resulting change in the conditions within the guide travels with the group velocity. In other words, if we pour energy into the wave guide and wait for it to come out of the far end, the time depends on the group velocity. And the group velocity is less than the speed of light, no matter how great the phase velocity. In fact, it turns out that in a wave guide the group velocity is equal to c^2 divided by the phase velocity. The greater the phase velocity, the less the group velocity; just above the cutoff frequency, where the phase velocity is almost infinite, energy is transmitted very slowly.

Thus although waves undeniably travel through wave guides at speeds faster than light, they produce no detectable result. This, however, is not always true. As a matter of fact, the very existence of long-range radio communication depends on the fact that radio waves in the ionized layers of the upper atmosphere have phase velocities greater than the speed of light. This is what enables them to be reflected by the ionosphere and to connect transmitters with receivers that are over the horizon.

The change in the speed of radio waves in the ionosphere is a result of their interaction with the free electrons there. The greater the concentration of free electrons, the greater the phase velocity. As in the wave guide, the velocity also depends on the frequency.

When a beam of radio waves enters the ionosphere at an angle, the increasing phase velocity and wavelength cause the beam to bend downward [*see bottom illustration on preceding page*]. Furthermore, since the electron concentration grows greater with height, the angle of refraction can increase to the point where the radiation is bent through an arc that brings it back out of the ionosphere and down to the ground again. (More accurately, the angle of refraction increases until the waves can undergo the process known as total internal reflection.)

Waves in the ionosphere behave very much like radiation traveling down a wave guide. There is a cutoff frequency that depends upon the electron concentration. The ionosphere is opaque to frequencies below the cutoff, while it passes the higher frequencies with phase velocities greater than c. As in the wave guide, the higher the frequency, the nearer the phase velocity approaches the normal speed of light, and the less the refraction. That is why waves of very high frequency are not reflected by the ionosphere and so cannot be received much beyond the horizon. They simply pass through the atmosphere without



FREE-ELECTRON DENSITY in a plasma can be determined by measuring increase in speed of radio waves passing through the gas. Microwave output of klystron is split into two parts, one passing through plasma, the other through a length of wave guide. Because of change in speed, waves are out of phase when they recombine in detector. Phase difference is read on oscilloscope.

Latest Analysis,
JULY 1, 1960

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BISMUTH	A-58		2	1		1	2						1*	
CADMIUM	A-60	1*	1*			1*								
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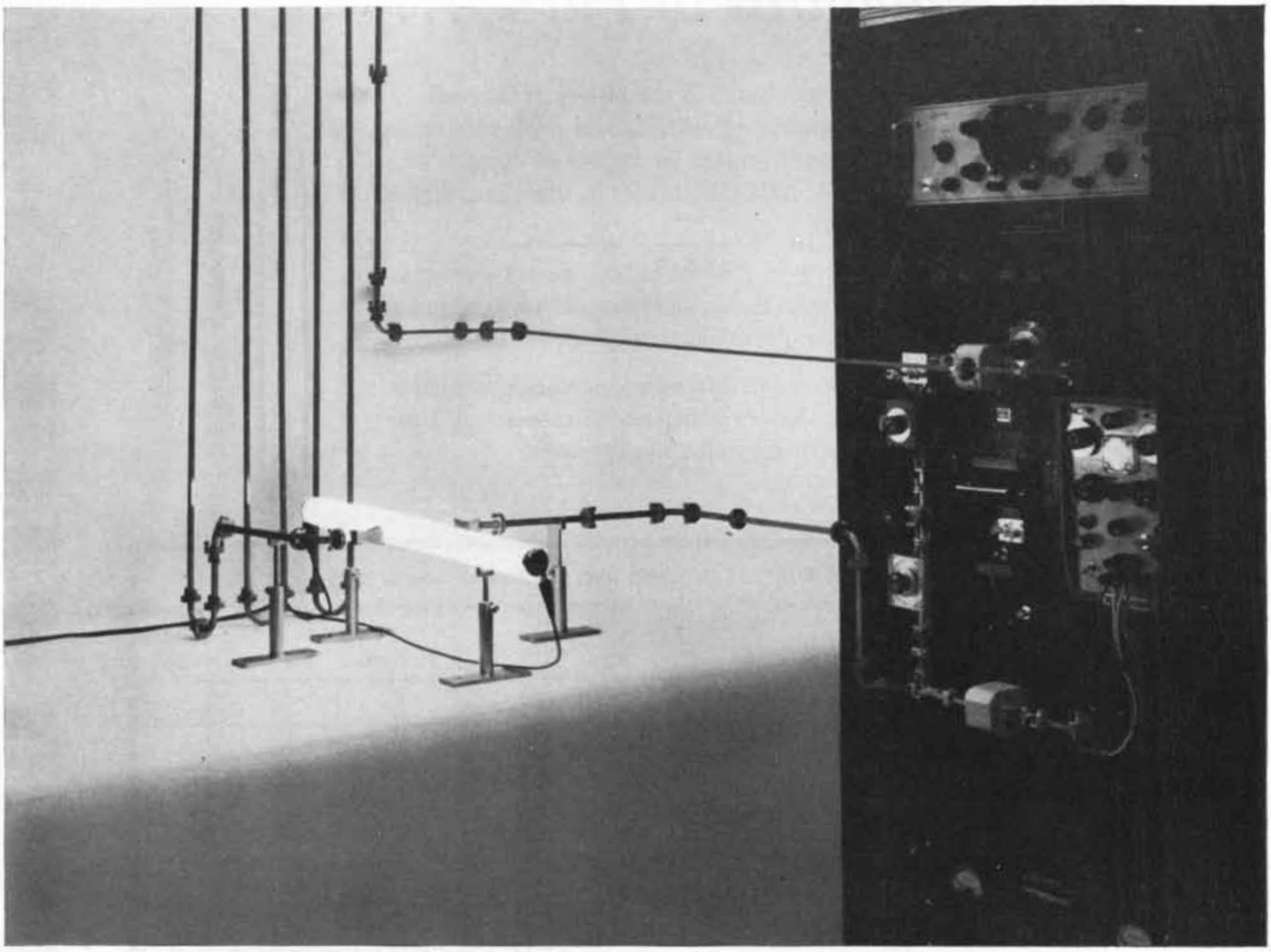
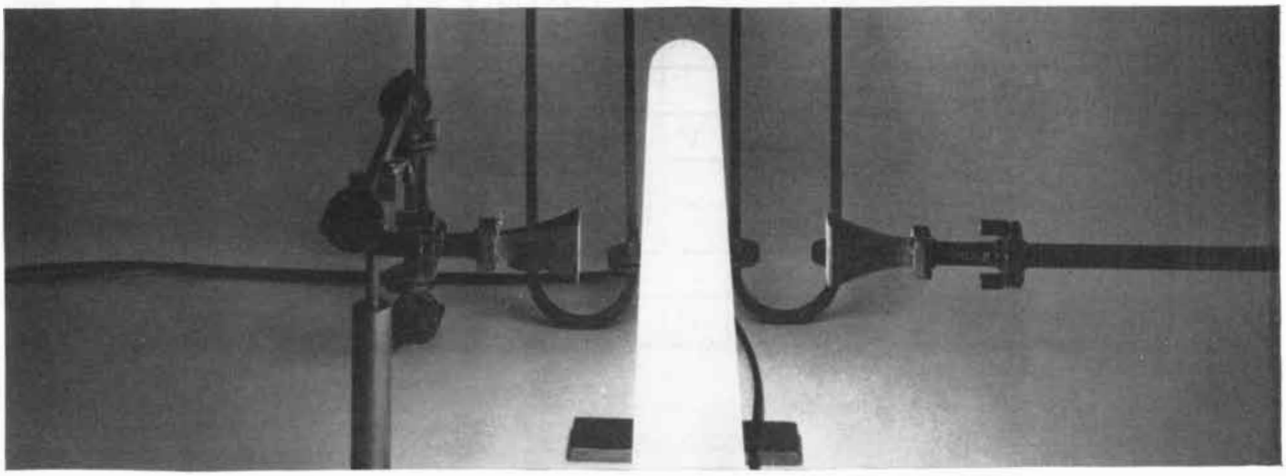
sufficient refraction to return them to the surface.

Radio waves are being used in current studies of the upper atmosphere to determine the electron density of the ionosphere. One way of doing this is to send up a rocket with a transmitter that emits waves of two frequencies, one low enough so that its wavelength is appreciably increased, the other high enough to be relatively unaffected. The two waves are in phase as they leave the transmitter, but the one with lower frequency travels through the ionosphere faster than the other. As a result, when they arrive at a receiver on the ground, they are no longer in phase. By following the difference in phase as the rocket rises, the electron density at various altitudes can be measured.

The ionosphere is an example of a type of fluid that is becoming more and more familiar; it is a plasma, or highly ionized gas, containing a mixture of positive ions and free electrons. In the atmosphere the plasma is produced by the action of the sun's radiation on air





PHASE-COMPARISON CIRCUIT for determining electron density is set up to make a measurement on the gas in a fluorescent lamp. Top photograph shows part of wave-guide sections (*vertical pipes*). Electronic equipment including klystron and detector are mounted on rack at right next to oscilloscope. Bottom photograph shows the microwave horns that send waves through the plasma.

Bendix Engineers use The University of Michigan Reactor to test radiation effects.

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summary of radiation-tolerant electronics

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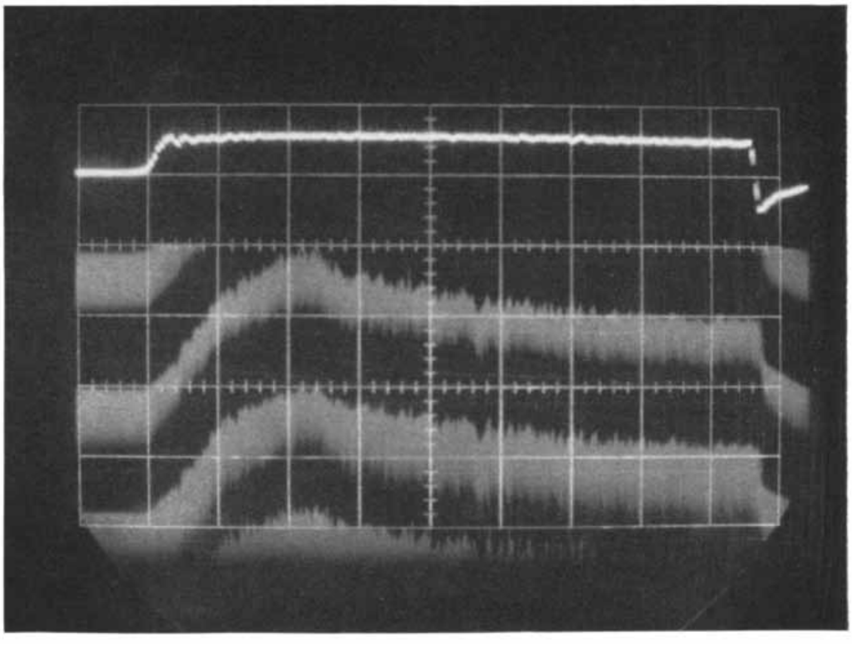
molecules. In earthbound laboratories, particularly those concerned with research in thermonuclear reactions, plasmas are made by passing powerful electrical discharges through gases in various types of device [see "The Stellarator," by Lyman Spitzer, Jr.; SCIENTIFIC AMERICAN, October, 1958].

To learn what happens inside the plasma after it has been produced, we must measure a number of its properties, including its electron density. We proceed in much the same way as in the ionospheric tests, but with one difference. In measurements on the ionosphere ordinary radio waves, with a frequency of a few megacycles per second, can be used, because they traverse thousands of feet of plasma. Within a laboratory device the available path length is generally only a few centimeters, so the probing radiation must have a wavelength that is still shorter, which means a frequency of tens of thousands of megacycles.

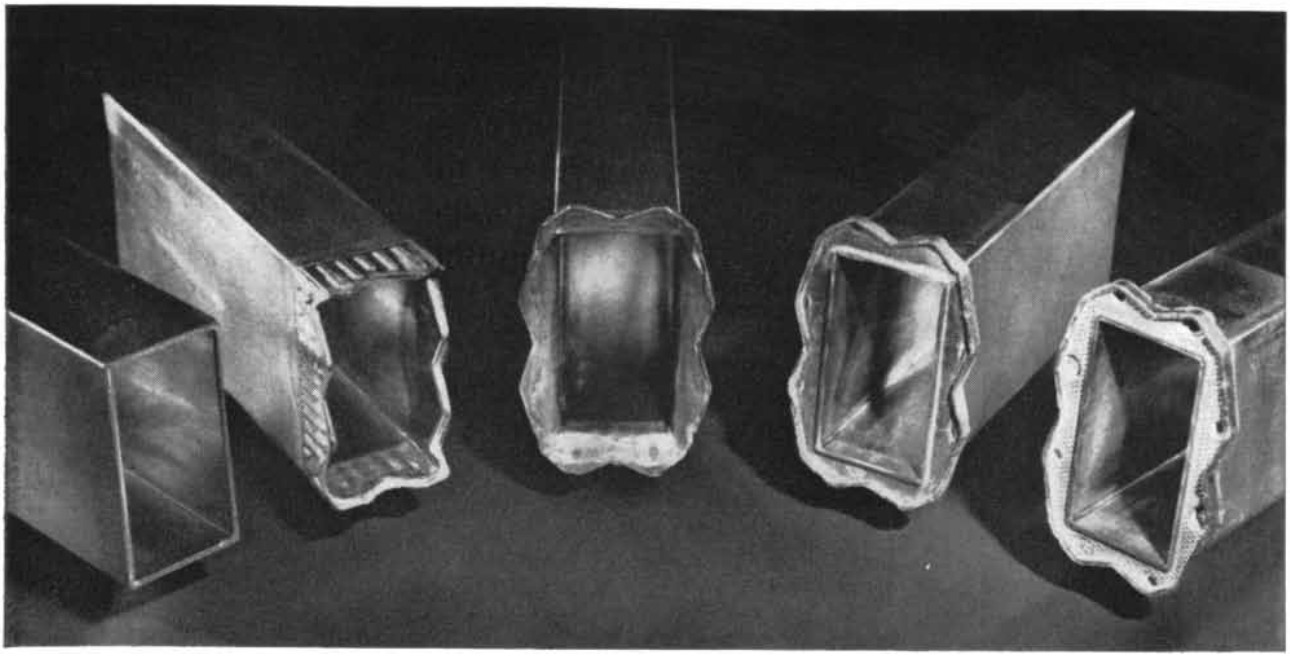
At Project Matterhorn, the thermonuclear project at Princeton University, we use four- and eight-millimeter microwaves in an arrangement similar to that of an optical interferometer [*see illustration on page 148*]. Radiation from a klystron tube is split into two beams, one passing through the plasma and the other through a known length of wave guide. When the beams are recombined, they show a phase shift, the amount of which depends on the electron density of the plasma. By monitoring the phase shift on an oscilloscope, the changes in electron density can be followed through the cycle of a heating pulse. The beauty of the method lies in the fact that it does not require putting a material probe into the hot gas, and so avoids contaminating the gas and otherwise disturbing the very effects under study.

Finally we should mention one other kind of wave that travels faster than light. It is the "particle wave" postulated by the French physicist Louis de Broglie in 1925. The waves that represent atomic particles also have phase velocities greater than c. But particles travel more slowly than light; again the apparent paradox is resolved by distinguishing group velocity from phase velocity. A particle is considered to consist of a packet of waves, which represents a superposition of many frequencies. This packet travels with the group velocity, and, as in the case of electromagnetic waves in a plasma or a wave guide, the group velocity equals the square of the speed of light divided by the phase velocity.

The group velocity is the only quantity that has physical meaning, particularly when we interpret the wave packet to represent the probability of finding a particle at a given point in space. The phase velocity of the de Broglie particle wave is strictly an abstraction, an intellectual invention, and is hardly mentioned in polite society these days.



OSCILLOSCOPE TRACES indicate electron density of plasma in the Stellarator. Narrow trace at top shows pulse of current used to ionize gas. Broad fringes below are formed by output of detector after recombining waves. Maximum vertical deflection of fringes, which occurs near left side, shortly after ionizing pulse starts, measures the electron density.



1 Waveguide cross-section before cold-flanging process.

2 First punch gathers the copper under extreme pressure.

3 The second starts flaring the metal to form eventual flange.

4 The third punch flattens copper into shape of finished flange.

5 The fourth embosses and completes flange. Time: approx. 50 sec.

Making cold copper flow like liquid

Waveguides — the metal tubes which carry microwave signals between an antenna and its transmitter or receiver — are used extensively in military radar and in the transmission of long distance telephone calls by radio relay. They must be manufactured to precise specifications, since a variation of only .003″ in their interior dimensions will cause serious microwave distortion.

This problem is complicated by the fact that as many as 100 individual waveguides may be used in connecting radio equipment with its antenna. Thus, not only must the waveguides be precisely engineered, but the connecting points must be constructed so that they offer no interference with the interior dimensions.

Connecting two or more waveguides is accomplished by use of flanges, or rims, on the ends of the tubes. Formerly, these flanges were separately manufactured and manually joined to the waveguides. The process was slow and costly, so Western Electric engineers developed a means of forming the flanges from the ends of the waveguides themselves. In doing so, they accomplished a metallurgical feat never before approached.

As a first step, the possibility of heating the waveguides and molding the ends into flanges was tried. This idea was not pursued since the heated copper annealed and lost its strength. The solution was to make the copper flow without heat — to crush it at such great pressure that the end of the tube would fold back and out in a fluid movement — *and do so without changing the inside dimensions of the tube.*

Development centered around the design of four high-precision forming punches with two complementary forming dies. Each punch was planned to take a step in the redistribution of the copper, with the dies acting as forming molds. To achieve the exact pressure and punching sequence required, it was necessary to design and build a special hydraulic press.

Here's how the process works: A waveguide is held in a fixed position in the press while the punches move in, out, and around, controlled by a revolving index head. The result of each punching stage is illustrated above.

This is believed to be the first time that precision metal tubing has been cold-flanged without distorting its configuration, and the first time that anyone has automatically produced waveguide flanges. The savings in time, labor and materials are substantial.

This break-through in metal-working, with all its many possibilities in other fields, is another example of Western Electric's progress in engineering developments.

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