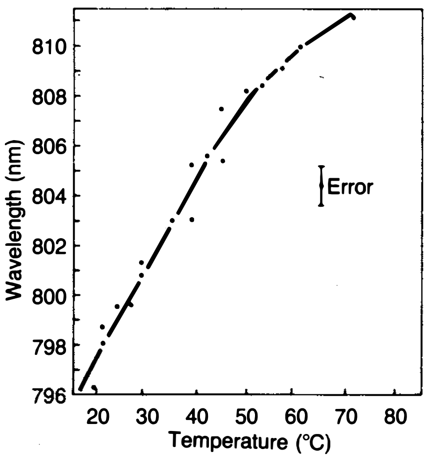
FIGURE 4
Emission wavelength of alexandrite varies with temperature



Alexandrite lasers show that heat is a form of electromagnetic action. The wavelength of light output by alexandrite solid-state lasers, can be varied by changing the alexandrite crystal temperature and hence its vibration, demonstrating that hydrodynamic effects are fundamental to the operation of the device.

Source: J. Walling, "Alexandrite Lasers," *Laser Focus*, Feb. 1982

the path to the target, providing important data for laser defense targeting systems.

Solid-state laser ceramics do have a property which yields tunable solid-state lasers from some materials, although not in ruby. In acting as a waveguide for flashlamp radiation in solid-state lasers, the ceramic crystal determines, in a way specific to each, the precise laser emission wavelength within a range determined by the dopant. This is because the energy transitions that produce coherent light involve not only the so-called electronic transitions of the dopant, but also involve, to some degree, the hydrodynamic, or vibrational characteristics of the crystal lattice. This is indicated by the fact that the same energy transition in chromium will produce different wavelengths of light, depending on the characteristics of the crystal in which it is imbedded. In ruby, the ^2E energy transition of chromium produces laser light at 694 nanometers; in alexandrite, a compound of ruby and beryllium oxide, the same transition produces light at 680 nm. (One nm is one billionth of a meter.)

To produce tunable solid-state lasers, what was required was a closer coupling between these vibrations of the crystal and the emission of the dopant. In a class of solid-state lasers known as *vibronic,* tunable vibrations of the ceramic crystal lattice, permit continuous tuning of the laser emission wavelength over a broad range. A group of laser physicists at Allied Corp. wrote: "The stimulated emission of photons is intimately coupled to the emission of vibrational quanta (phonons) in a crystal lattice. In these 'vibronic' lasers, the total energy of the lasing transition is fixed, but can be partitioned between photons and phonons in a continuous fashion." In the case of Allied's alexandrite laser, this property enabled development of a solid-state laser, continuously tunable over the range of 700-818 nm.

Confirming the close relationship between heat and coherent light, alexandrite's emission wavelength is tunable by varying the temperature of the crystal (**Figure 4**). The close coupling between light (photons) and heat or vibrational energy (phonons) in alexandrite, clearly demonstrates that light, heat, and sound are each forms of electromagnetic action.

In addition to displaying the vibrational hydrodynamic

Leonardo da Vinci and the hydrodynamics of surfaces

The concept of "surface of discontinuity," conceived by Leonardo da Vinci and elaborated hundreds of years later by German hydrodynamicist Ludwig Prandtl (1875-1953), provides a valuable framework for investigating the action of flowing gases, fluids, or solids, over a material surface. The "surface of discontinuity" is a boundary of stationary fluid around a body, whose integrity affects whether or not the flows that a surface is subjected to, can damage it.

Leonardo and Prandtl both established that the formation, development, and characteristics of the "surface of discontinuity" between fluids, gases, and solids, are fundamental to determining the subsequent evolution of hydrodynamic action. Dino de Paoli provides a detailed account of their work in "Leonardo da Vinci and the True Method of Magnetohydrodynamics," in the January-February 1986 issue of *Fusion*.

Using water surface as an example, Leonardo discussed how the surface of discontinuity is distinct from both substances it separates:

> The surface of a thing is not part of it. . . . It must needs be therefore that a mere surface is the common boundary of two things that are in contact: Thus the surface of water does not form part of the water, nor does it consequently form part of the atmosphere. . . . What then divides water from air? There should be a common boundary which is neither air nor water. . . . Therefore they are joined together and you cannot raise up or move air without the water. . . . Therefore a surface is the common boundary of two bodies which is noncontinuous and does not form part of either. (Arundel Collection, 159v)

properties of simple water waves that do not transport matter, waves akin to shock waves that *do* transport matter occur in solids in crack propagation or fracture. Although cracking appears to occur "instantaneously," it actually propagates through a material at a measurable rate. Since such waves are catastrophic for a machine part—for example, fracture of a ruby rod under high intensity flashlamp radiation—it is a priority to find a solution to such destructive shocks. The solutions discovered to date are hydrodynamic in nature.

One type of such destructive waves occurs when materials are subjected to "thermal shock," that is, cooling from high temperatures, resulting in the material passing through one or more crystalline phase transformations which can each produce cracking. Strengthening materials against thermal shock, or against other uncontrolled effects of phase transformations, is the focus of much research, and is referred to as "transformation-toughening."

Ceramic refractory brick in iron and steel furnaces provides a good example of *poor* thermal shock resistance. The purpose of refractory brick is to reflect as much heat as possible back into the furnace, and at the same time to present a low enough temperature to the steel shell enclosing the brick walls, that the furnace is not destroyed. Obviously, the brick must be stable at high temperatures.

Prandtl applied this principle to the study of the flow of fluids over surfaces. He wrote:

> Surrounding the surface of the solid body there is a thin layer where the velocity gradient generally becomes very large, so that even with very small values of the velocity the shear stresses assume values that cannot be neglected. (*Applied Hydro- and Aeromechanics*, Dover, New York, 1934)

These "shear stresses" are expressed in vortex formation:

> any small internal friction changes the discontinuity in velocity into a gradual transition in a layer with rotation. In the domain in which this continuous change takes place we have a layer of vorticity formed out of vortex filaments. . . a surface of discontinuity may therefore be considered as a surface distribution of vortices, i.e., a vortex surface. (*Fundamentals of Hydro- and Aeromechanics*, Dover, New York, 1934)

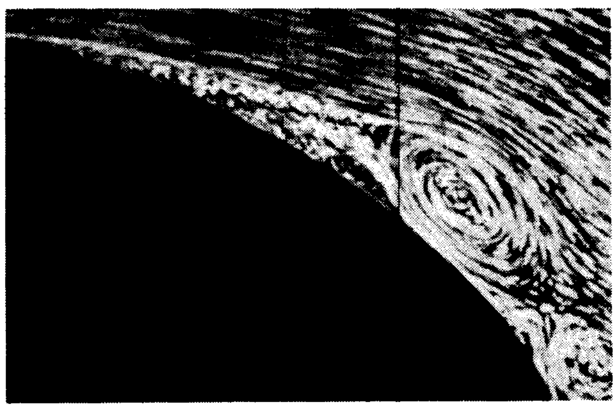
The effect is that the surface of discontinuity itself begins to rotate, until finally, the flow over it literally *rips* the fluid boundary layer off the surface, in some cases, carrying part of the solid surface along with it. The figure shows a "vortex surface" in the movement of water around a cylinder, just before the boundary layer is torn off. The high frequency vortices that flow over surfaces subjected to high energy flux, illustrate why a wavelength can always be associated with a given energy flux density.

Leonardo also recognized that the principal means of hydrodynamic energy transfer is vibration, i.e., wave action that does not transport matter:

> if you cast two little stones . . . in water, you will see two separate quantities of circles . . . which growing, come to encounter each other, one circle intersecting the other, always maintaining for centers the places struck by the stones. The reason is that although there is some evidence of movement, the water does not leave its location, because the opening made in it by the stones closes up again at once and this motion made by the sudden opening and closing produces a certain shaking, which can be called trembling rather than motion. . . . take heed of those straws which by their lightness stand on the water; notwithstanding the wave made under them by the coming of the circles, they do not leave their first locations. (Institut de France Ms. A 61r)

As the accompanying text documents, these are the hydrodynamic principles which underlie advanced industrial and aerospace materials.

Rotation of boundary layer about a cylinder



This photograph shows a moment in the evolution of the surface of discontinuity on a cylinder into a "vortex surface," as water follows around the cylinder, just before the boundary layer is torn off.

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