search & discovery

Tunable coherent infrared techniques show progress

Recently several groups have produced tunable coherent infrared sources; some of these sources are tunable over a broad range of wavelengths. They vary in their ability to be continuously tuned. The most novel of these sources was reported by James J. Wynne in an invited paper at the Washington meeting of the American Physical Society on 23 April. Wynne, Peter Sorokin and John Lankard, all of IBM Research Center, reported[1] that they had produced a continuously tunable source over the range 2–24 microns with no apparent fundamental limitation to achieving longer-wavelength generation. Groups at MIT National Magnet Laboratory, Bell Laboratories, Rice University and the University of California at Berkeley have all recently reported on tunable coherent infrared sources.

These sources have many applications. They can be used to study elementary excitations in solids and complex biological molecules. A number of air pollutants show strong absorption in the infrared. It has been suggested that because molecules of different isotopes of the same element have different vibrational frequencies, one could achieve efficient and economical separation of these isotopes. For astronomy the sources could be used as a tunable local oscillator in a heterodyne system.

In the IBM experiment beams from two separate dye lasers, which are pumped simultaneously by a nitrogen laser, interact within a chamber of alkali vapor, the vapor being maintained in a heat-pipe oven. Each dye laser can be tuned from about 0.36 to 0.7 microns by using different dyes and diffraction gratings. The experimenters used a "four-wave parametric" conversion technique (see figure on page 20). Most of the work was done with potassium. The first dye laser is chosen so that its output wavelength is tunable in the neighborhood of the 4s–5p resonance lines of potassium. The beam does three things: It provides one of the waves needed in the four-wave mixing process; it generates a second wave needed for the four-wave process by inducing stimulated electronic Raman emission and producing a Stokes wave at a frequency $\nu_S = \nu_L - E(5s)/h$ it allows the four-wave mixing process to become phase matched through fine adjustments of its frequency.

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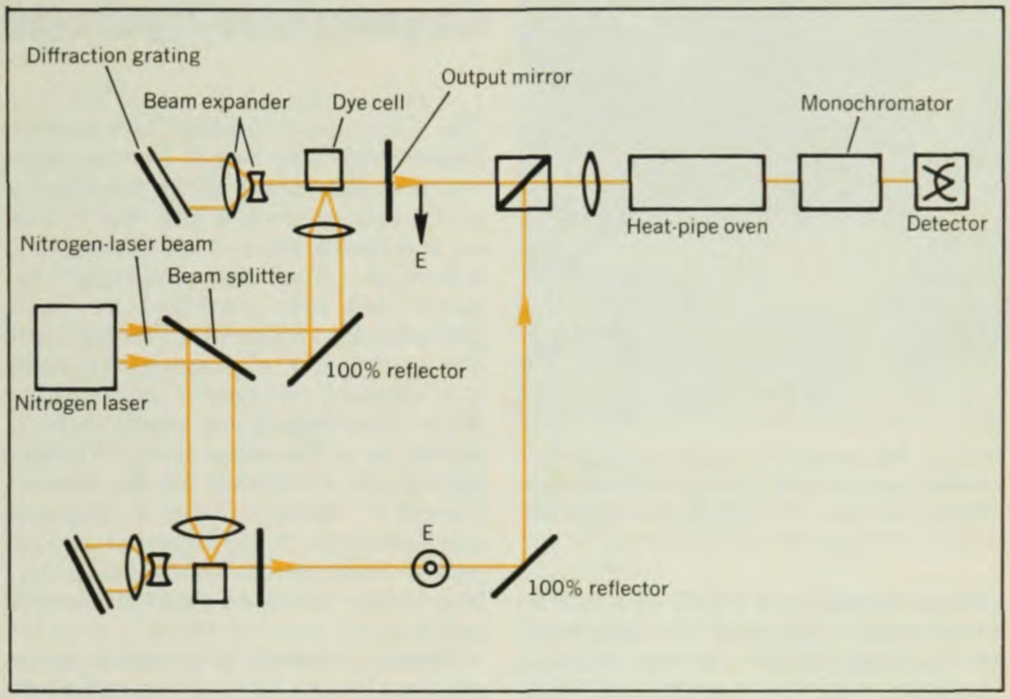


Tunable coherent infrared source has two dye lasers pumped by a nitrogen laser. The beams interact within a chamber of alkali vapor. The dye lasers are tunable by using different dyes and diffraction gratings. The source is tunable from 2–24 microns.

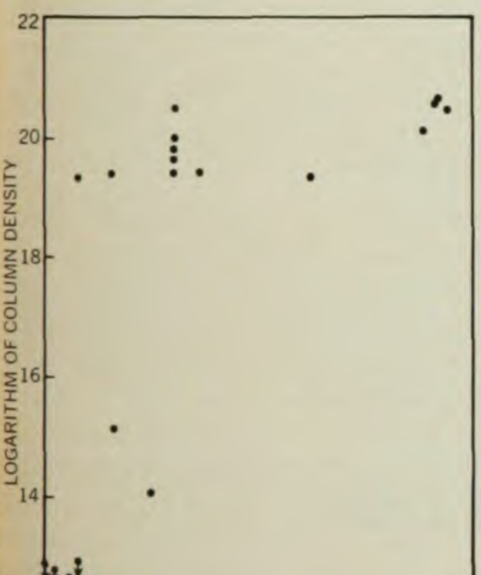
Ormak nears collisionless regime

The Ormak experiment at Oak Ridge National Laboratory has advanced appreciably toward the so-called collisionless regime in studies that increase the expectation for reaching the "reactor regime" without damaging loss from instabilities. Plasma ions have travelled about five to ten times around the torus before scattering 90 deg, and no new anomalous effects were observed. The result gives increased confidence that no additional empirical components are needed to explain the scaling of ion temperature in this regime, that the same combination of the classical laws of atomic and plasma physics plus empiricism (pseudoclassical scaling) hold true here as in previous experiments. Ormak was able to reach a higher degree of collisionlessness, although the ion temperatures reached did not necessarily exceed temperatures reached in some other experiments, because of its fat-doughnut geometry. These results were described at the March meeting on toroidal plasma confinement in Garching, Germany.

Ormak is a toroidal ohmically heated confinement device with a low aspect ratio: The ratio of major radius (79.5 cm) to minor radius (23.5 cm) is only 3.4. A set of 56 equally spaced copper coils can supply a maximum toroidal field of 25 kG to confine the plasma, and the maximum peak plasma current is about 400 kA. The reported studies were done over a range of experimental parameters; for example, a typical study was done at 18-kG toroidal field, and a plasma current of 120 kA had an ion temperature of 350 eV, a 800-eV electron temperature, a peak electron density n of 5×10^{13} cm^{-3} and a confinement time τ of 15 millisec. Among the diagnostic tools that were used to analyze the plasma parameters were Thomson scattering (electron-energy profiles), charge exchange (ion temperatures) diamagnetic loops (changes in plasma pressure), soft x rays (peak electron temperature) and microwave interferometry (average electron density).

Deep penetration into the collisionless regime is considered an important feasibility test for toroidal confinement systems: In a reactor, the mean free al to the amount of obscuring material in the form of solid particles between us and the star. To quantitatively determine the color excess, the star's brightness is measured in blue light, then again in yellow light, then the ratio is taken and it is compared with what it would be for an unreddened star of the same spectral type. If the blue light is diminished with respect to the yellow, it is due to the selective extinction by small solid particles that absorb more in the blue than in the yellow.

The Princeton group observed 23 stars. Eight of them were unreddened and had an upper limit to the ratio of molecular to atomic hydrogen of 10^{-7}, in agreement with theory. The remaining 15 had different reddenings. One of them is relatively unreddened but still shows a lot of molecular hydrogen. Two of them are somewhat reddened and show only a small amount of molecular hydrogen. If a color excess of 0.10 is taken as a boundary line for color excess, then there are 11 such stars, and they show that the fraction of hydrogen atoms bound in molecular form ranges from 0.08 to 0.67. Salpeter and his collaborators had predicted that more than 10% would be in molecular form, but their calculation was for a spherical cloud. As Spitzer points out, since the ratio of molecular hydrogen is less than 10^{-7} in unreddened stars, over the large dynamic range involved the difference between 10% and 67% does not appear to be significant. In a general way the observations do agree with theory.



Copernicus results for molecular hydrogen amount in stellar clouds between Earth and 23 different stars. Column density is number of molecules in a column, 1 cm^2 in cross section, extending from Earth to the star; the color excess measures the reddening of a stellar spectrum produced by small solid particles. Points shown with downward arrows represent upper limits. Note the all-or-nothing effect.

One well known astrophysicist commenting on the molecular-hydrogen results said that problems associated with clouds and the interstellar medium are generally very complicated and difficult. In this case the theory succeeded in predicting an effect over many orders of magnitude. "That's just spectacular," he concluded. —GBL

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Tunable infrared sources

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A third wave, ν_P, is provided by the second dye laser. The waves ν_L, ν_S and ν_P beat together to create a polarization at

$$\nu_R = E(5s)h - \nu_P = \nu_L - \nu_S - \nu_P$$

This polarization can radiate, thus providing a tunable infrared output, because the frequency of the second laser is tunable.

As originally reported,[2] with the use of one vapor (potassium) alone, tunable infrared output was limited to the range about 2–4 microns. This range was determined by the fact that the first dye laser had to be simultaneously tuned to generate high-intensity Raman light and yet satisfy the phase-matching condition for the four-wave mixing process. However, by the addition of a second non-resonant alkali-metal vapor (sodium) to provide linear dispersion, the phase-matching condition can always be satisfied with the first dye laser tuned for maximum Raman–Stokes generation. In this way, by "biasing" the vapor for long-wavelength output, the IBM group generated[1] coherent infrared over the range 2–24 microns.

The two-laser method extends the tuning range of the dye laser, which was previously tunable only from the near-ultraviolet, across the visible spectrum and into the near-infrared to about 1.2 microns.

The technique produces peak powers between 0.1 and 100 milliwatts, using a 100-kW nitrogen laser pump. The infrared output is proportional to the cube of the pump power; thus a 1-MW nitrogen laser is expected to increase the infrared output by 1000.

In a related experiment, Sorokin, Wynne and Lankard have also generated laser infrared at a number of discrete wavelengths in the range 12–220 microns, forming a "picket-fence" spectrum. This is done by tuning the second harmonic of one dye laser to various resonance lines in potassium.

The IBM group told us that among the advantages of their scheme are the continuously tunable nature of the output (that is, it does not display mode hopping) and an absence of the need for cryogenic temperatures.

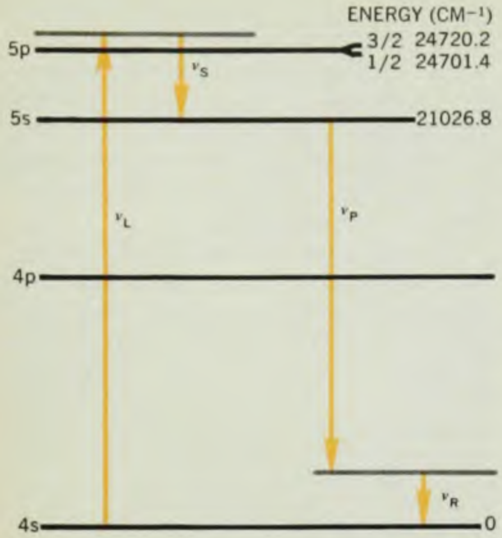
At Bell Labs Kumar Patel and his collaborators have been using two carbon-dioxide lasers to obtain step-tunable far-infrared radiation, work first discussed by them[3] in 1969. Now T. J. Bridges and Van Tran Nguyen of Bell reported at the March meeting of the American Physical Society that they have used one carbon-dioxide laser to pump a spin-flip Raman laser, producing a source that is tunable from 80 to 120 microns.

In a spin-flip Raman laser, a magnetic field is applied to an indium-antimonide sample. Raman scattering occurs when the conduction electrons in the crystal flip their spins in the magnetic field, B. The frequency ω_S of the shifted light varies as $\omega_S = \omega_0 - g\mu_B B$; ω_0 is the pump frequency, μ_B is the Bohr magneton, and g is the effective gyromagnetic ratio of the electrons in indium antimonide.

When the carbon-dioxide laser pumps the spin-flip Raman laser, two frequencies come out—ω_0 and $\omega_0 - g\mu_B B$. The radiation enters a second indium-antimonide crystal and difference-frequency mixing occurs, resulting in an output of frequency $g\mu_B B$. The output is tunable because the magnetic field can be varied.

The Bell experimenters have produced output powers of about 1 microwatt with a pulse repetition frequency of about 400 times per second, an average power of 10^{-8}–10^{-9} watts. Patel notes that this power is more than sufficient to do any kind of spectroscopy desired. The group has measured the absorption of carbon monoxide with a signal-to-noise ratio of about 10 000. There is not enough power to do further nonlinear optics, however. To do that they will need to increase the input power, since in a difference-frequency mixing experiment, the output is proportional to the product of the two input powers.

In the spectroscopic measurements the Bell group's narrowest lines are about 0.1 cm^{-1}. The line width arises because the spin-flip Raman laser is not continuously tunable; it has its own modes, which are separated by about 0.1 cm^{-1}. Patel notes that this is very close frequency spacing, at least compared to doing difference-frequency mixing between two carbon-dioxide lasers. In the present spin-flip Raman laser the crystal faces are parallel so that light bounces back and fourth, making the crystal act like the modes of a cavity. On the other hand, tilting



Four-wave parametric mixing in potassium. The waves ν_L, ν_S and ν_P beat together to create a polarization at $\nu_R = \nu_L - \nu_S - \nu_R$.

one of the ends of the crystal eliminates the cavity effect, and a superradiant spin-flip Raman laser, which is essentially a single-pass device, is produced. Nguyen is trying this arrangement now, using a pumping laser with enough intensity to produce enough single-path gain through the sample to build up intensity of the Raman-scattered light from spontaneous emission so that the device can be continuously tuned without mode hopping.

In principle the Bell technique should be applicable over a much wider range. Using two fixed-frequency carbon-dioxide lasers Patel and his collaborators had earlier shown that one could go from 2 cm^{-1} to 140 cm^{-1}. So Patel believes that with the new technique they should be able to tune in the range from 1 mm to 70 microns.

At MIT's National Magnet Laboratory R. L. Aggarwal, Benjamin Lax and their collaborators have demonstrated an infrared tunable source in the 5-micron region in which they combined a high-power spin-flip Raman laser with a 10.6-micron carbon-dioxide laser to produce the sum frequency. To bridge the far-infrared-microwave gap, they extended this general technique to produce the difference frequency. This was accomplished by a noncollinear technique of phase matching in gallium arsenide. The group reported their results in the 1 April issue of *Applied Physics Letters.*[5]

In more recent results reported at the March APS meeting in San Diego, the group produced step tuning using two carbon-dioxide lasers; they obtained 60 lines from 70 microns to 2 mm. Lax told us that it is evident that if one uses gratings for both carbon-dioxide lasers, it is possible to obtain 3000 lines between 70 microns and 1 cm.

In the present experiment one laser has 30 kW of peak power and the other 100 kW of peak power. The output observed was about 1 milliwatt at 100 microns; the MIT group had calculated that they would obtain 700 milliwatts. In work now in progress, the group is making a number of obvious engineering improvements that they expect will enhance the peak-power capability by two orders of magnitude and the repetition rate from three per second to at least ten per second. Using these improvements and a 1-kW spin-flip Raman laser that they had developed earlier, the group expects to obtain continuous tuning for the difference frequency.

At the March meeting the group also reported on a scheme to produce cw operation by employing a collinear phase-matching technique that takes advantage of a periodic variation of the refractive index.

Other groups. In the same issue of *Applied Physics Letters* that carried the MIT report was an article[6] by C. D. Decker and F. K. Tittel of Rice University on difference-frequency mixing between the output from a tunable narrow-linewidth ruby-pumped infrared dye laser and a Q-switched ruby laser in a proustite crystal. The Rice experimenters obtained peak infrared powers in the kilowatt range; they told us that their source was tunable from 3.20 to 6.47 microns. They believe that by using proustite crystals cut at a different angle to the optic axis, tunability from 6.47 to 13 microns should be possible.

In a more recent experiment, Decker and Tittel have used two independent dye lasers, mixing them in a proustite crystal and obtained tunability from 5.82 to 7.25 microns with peak powers in the 20–100-watt range. Provided appropriate nonlinear mixing crystals can be found, they say that this dual dye-laser frequency-mixing arrangement could generate radiation from 5 microns to greater than 100 microns.

At the March APS meeting, Patrick Yang, James Morris, Paul L. Richards and Yuen-Ron Shen of the University of California at Berkeley reported generation of continuously tunable far-infrared radiation over a factor of 20 in wavelength from 52 to 2000 microns. In these experiments the laser source was a one-dye-cell dual-beam dye laser. The laser cavity contains two diffraction gratings to tune, individually, two orthogonal polarizations of laser light that are spatially separated by a Glan-Thomson prism. This arrangement minimizes alignment and synchronization problems. Using a ruby-laser pump, the dye-laser output is 300 kW in each beam. Collinearly phase-matched far-infrared generation in room-temperature lithium niobate and zinc oxide yields about 5 milliwatts of far-infrared power from 52 to 800 microns. The power falls below 1 milliwatt at 2000 microns. These power levels are more than adequate for spectroscopy in the energy-starved far-infrared region of the electromagnetic spectrum, Richards said.

Tuning is achieved by rotating one of the laser gratings and simultaneously changing the angle of the nonlinear crystal. The tuning range can be extended to shorter wavelengths by using other nonlinear crystals. —GBL

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NBS offers 5 reference temperatures under 8 K

A superconductive device that provides five fixed-point reference temperatures near absolute zero has been developed at the National Bureau of Standards. The device, which will reproduce its transition temperatures within 1 millikelvin, is made from five high-purity elements—lead, indium, zinc and cadmium—and provides fixed points near 7.2 K, 3.4 K, 1.2 K, 0.8 K and 0.5 K.

Cylinders of the five elements are mounted in a threaded copper stud and enclosed by a mutual inductance coil set. The whole unit is about 1.5 cm in diameter and 4 cm long. In use, the copper stud is connected thermally to the thermometer to be calibrated or to the experimental chamber, and the four mutual-inductance coil leads are connected to a mutual-inductance bridge. The superconductive transitions can be easily monitored by mutual-inductance measurements, according to NBS. Called SRM 767, the device is available through the NBS Office of Standard Reference Materials for $250.00 each.

in brief

The first test experiments using the University Isotope Separator-Oak Ridge (UNISOR) were recently carried out with 100-MeV nitrogen ions on thin Nb^{93} foils mounted as part of the wall of the ion source. Recoil atoms were stopped in the ion source of the separator. Cadmium isotopes of mass 101 to 103 were definitely identified. When completed, a short tape-transport system will be attached to an extracted beam station for studies of still shorter-lived isotopes. □