*Physica* 41 (1969) 198-208 © *North-Holland Publishing Co., Amsterdam*

# COHERENT DETECTION SPECTROSCOPY

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Received 5 November 1968

**Synopsis**

Various methods of optical spectroscopy are compared, with special emphasis on resolution and acceptance of the systems. It is shown that coherent detection with a laser as a local oscillator has important advantages for specific applications in astronomical spectroscopy and interferometry, especially in the infrared. The merits and disadvantages of coherent detection systems are numerically evaluated, and a recently developed laboratory system is briefly described. Future applications in stellar spectroscopy and interferometry are enumerated.

1. Comparison *of spectroscopic techniques.* The various methods of spectroscopy currently in use or under development can be characterized by three quantities: resolving power $R$, optical acceptance $L$ of the optical system (that is flux received by detector divided by incident luminance), and signal to noise ratio of the detector, obtained with a given source intensity. *Dispersive systems* (prism, grating) are characterized by a theoretical resolving power $R_0$ that is proportional to the size of the dispersive element w :

$$R_0 = W \frac{\mathrm{d}n}{\mathrm{d}\lambda} \qquad \text{(prism)}$$

$$R_0 = W \frac{\sin i + \sin u}{1} \qquad \text{(grating)} \tag{1}$$

where $\lambda$ is the wavelength, $n$ the index of refraction and $i$ and $u$ the angles of incidence and diffraction. The actual resolving power $R$ is less because of the influence of the slits, unavoidable in these types of instruments. Since $W$ is in practice limited to the order of 10 cm, $R_0$ is never much higher than $10^5$ for visible light, and less in the infrared. When $\beta$ is the angular height of the entrance slit (slitwidth divided by focal length), acceptance and resolving power are mutually related by (see ref. 1)

$$LR = \tau\beta A, \tag{2}$$

where $\tau$ is the transmission factor (small in dispersive spectrographs) and A is the effective area of the dispersive element; the $LR$ product that ultimately can be reached is of order 1 $cm^2$.

The various types of Fabry-Perot and related interferometric devices have two advantages over dispersive devices. The resolving power is now independent of the size of the element, and is given by

$$R \approx R_0 = Nm, \tag{3}$$

where N is the finesse of the interferometer, solely determined by the reflectivity $r$ of the reflectors according to

$$N = \frac{\pi\sqrt{r}}{1 - r}, \tag{4}$$

and m is the order of interference. In practice N is usually about 50, whereas m can be as high as $10^4$, so that resolving powers of $10^6$ can be reached, even in the infrared. The acceptance of an interferometric system is no longer reduced by slit effects, hence luminosity and resolving power are now related as

$$LR = \tau A, \tag{5}$$

which may be as high as 50 $cm^2$, and consequently also the acceptance is much higher, since in practice slit optics with $\beta$ greater than 0.05 is never encountered.

This type of interferometer is very sensitive to misalignment. A recently developed version, the confocal F.P., is not. Consequently higher orders of diffraction and greater resolution is reached, and the acceptance is enhanced also. For either type of instrument the spectral range covered is quite small, *viz.*

$$Ail = \lambda/m. \tag{6}$$

*Fourier* transform spectroscopy, using a Michelson type interferometric system with a moving mirror, combines the advantages of the interferometer with an even higher effective luminosity. The resolving power is given by

$$R \approx \Delta/\lambda, \tag{7}$$

where A is the range of the moving element, and again not limited either by size or by slit effects. The acceptance is in principle similar in magnitude to that of the interferometer, but because the spectral range is now no longer limited by the order of diffraction, and all spectral elements $\delta\lambda$ are studied simultaneously (multiplexing), in practice the measuring time needed to obtain information about all spectral elements required is much higher than of a Fabry-Perot interferometer; the gain in effective acceptance is of the order

$$\sqrt{M} = \sqrt{\frac{\lambda_1 - \lambda_2}{\delta\lambda}},$$

when $\lambda_1$ and $\lambda_2$ are the extreme wavelengths of the spectrum range to be investigated. The angular aperture of a Fourier transform interferometer, like that of a planar F.P., is limited in inverse proportionality to $1/\sqrt{R}$. So far, *RL* products of order $10^4\,\mathrm{cm}^2$ have been reached.

The various expressions for the theoretical resolving power used here are all special cases of the formula

$$R_0 = \frac{\partial\Delta s}{\partial\lambda}, \tag{8}$$

where As denotes the optical path difference between extreme rays through the system. It is therefore not surprising that higher resolutions than about $10^7$ in the infrared can not be reached by any of these methods with instruments of reasonable size and within measuring times of practical interest.

Since also in the systems mentioned so far acceptance and resolving power are more or less inversely proportional to each other, a very high resolving power can only be obtained when at the cost of a low acceptance. This poses certain problems on the detector which are not so much of an optical as of an electronic nature. It is therefore useful to investigate methods which can overcome the optical limitations by not using any dispersive or interferometric system at all, but consider direct spectral sensitive detection with as low a noise equivalent power as possible. Only in this way the acceptance-resolution restriction might be expected to be broken down, although of course with a high resolving power always other restrictions will remain coupled, the most important of which are a limited spectral range and, in view of the small amounts of power received, a long observing time.

A very promising, very high resolution spectroscopic method is the *atomic beam resonance spectroscopy*, originally proposed by Blamont and Roddier, and realized by the latter [2]. Here, resonance fluorescence of suitable metal vapour resonance lines is used at the same time as analyzing and as detecting principle; the resonance wavelength is shifted over a very limited range by means of a magnetic field, and the fluorescence due to incident radiation is measured. The resolving power is now determined by the Doppler-width of the resonance absorption line, and by using heavy atoms (strontium or barium), values of $R \approx 10^7$ have been reached in the red part of the visual spectrum. The performance of such a system is rather low, because of the small fluorescence efficiency (of order 0.3%) and the many windows and filters required in the system. A transmission factor of only 1.5% is quoted, yielding an acceptance of about $10^{-6}\,\mathrm{cm}^2$ and therefore an *RL* product of 10 $\mathrm{cm}^2$ to be compared with $10$–$50\,\mathrm{cm}^2$ for a Fabry-Perot interferometer and with about 1 $cm^2$ for a grating. The overall performance is thus comparable to that of a dispersive system, and might be made even better by using a more sophisticated optical filtering device. The available spectral range is determined by the magnetic field strengths that can reasonably be applied; in practice it is of the order of a few angstrom units only, sufficient though for many astronomical purposes.

In table I the performances of the various spectroscopic systems discussed have been collected. The last column gives an estimate of the relative spectral range.

TABLE I

Comparison of the maximum attainable performance of spectroscopic systems (orders of magnitude only)

| Type | Resolving power | Optical acceptance | $RL$ product | Relative spectral range |
|---|---|---|---|---|
| Prism | 105 | $10^{-5}$ $cm^2$ | 1 $cm^2$ | 1 |
| Grating | $10^6$ | $10^{-5}$ | 10 | $10^{-1}$ |
| Fabry-Perot planar | $10^6$ | 5.10-5 | 50 | $10^{-3}$ |
| Fabry-Perot confocal | 107 | 10-4 | 103 | 10-4 |
| Fourier-transform | 107 | 10-3 | 104 | $10^{-1}$ |
| Atomic beam | 107 | 10-s | 10 | 10-3 |
| Coherent detection | 103 | 10-3 | $10^5$ (for point sources) | ? |

2. *Coherent detection*. From the theory of detection of electromagnetic radiation it is well known that by far the smallest minimum detectable power is obtained by using superheterodyne detection methods in conjunction with suitable fast detectors (semiconductor diodes or photomultipliers). The signal to noise power ratio for incoherent detection is the ratio of the square of the signal generated current $I_s$ or power $P_s = (h\nu/e)\, I_s$ to the total shot noise, and is given by

$$(S/N)_{\rm incoh} = \frac{\eta^2 I_s^2 M^2(\omega)}{\{2e(I_D + \eta I_s)\, M^2 + I_R\}\, \Delta f} =$$

$$= \frac{\eta^2 P_s^2 M^2}{h\nu\{2e(P_D + \eta P_s)\, M^2 + P_R\}\ A f} \tag{9}$$

where $I_D$ and $P_D$ are the thermal dark noise current and power, and $I_R$ and $P_R$ the noise equivalent current and power of the amplifier following the detector, respectively. $M$ characterizes the frequency response of the detector and Af is the rf noise bandwidth of the amplifier. The minimum detectable power $(P_{\rm min})_{\rm incoh}$ is at high frequencies limited in practice by the thermal noise of the receiver current, given by $I_R = 2kT/eR$ where $R$ is the input resistance. Making this simplification and putting $(S/N)_{\text{incoh}} = 1$, we find

$$(P_{\min})_{\text{incoh}} = \frac{h\nu\Delta f}{\eta}\left(\frac{4kT}{M^2e^2R\Delta f}\right)^{\frac{1}{2}}. \tag{10}$$

Coherent detection is obtained by letting the temporally incoherent optical wavetrains to be measured and the coherent signal of a laser beam of comparable frequency mix on the photocathode. As is well known, the photocell measures the square of the amplitude of the total light signal, and in this the difference frequencies between the monochromatic laser signal and the optical signal to be measured are represented. In the photocurrent additional noise occurs, the frequency distribution of which is a faithful copy of that

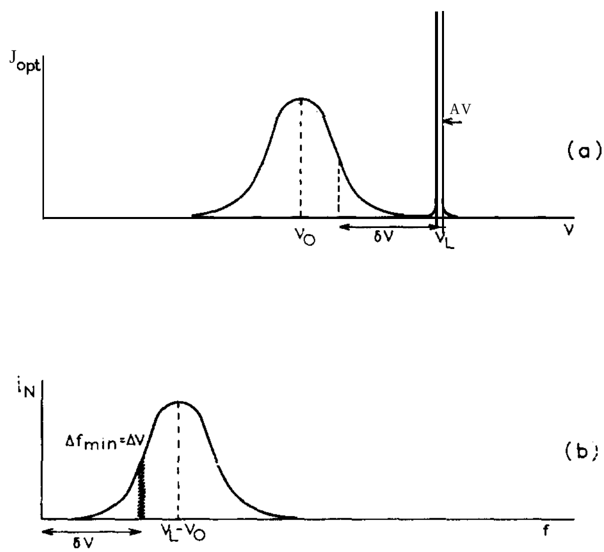


Fig. 1. To illustrate the principle of coherent detection :
a) optical signals, b) frequency distribution of induced noise.

of the optical signal, only the frequencies are now distributed around the average difference frequency of both signals. From the optical range they have been shifted to the radiofrequency range and can now be suitably amplified (fig. 1). The signal to noise ratio of a coherent detection system is given by

$$(S/N)_{\text{coh}} = \frac{2\eta^2 I_s I_L M^2}{\{2e(I_D + \eta I_s + \eta I_L)\, M^2 + I_R\}\, \Delta f}, \tag{11}$$

and when care is taken that the laser intensity is much stronger than the signal intensity, and that the laser induced shot noise dominates all other noise, this expression reduces to

$$(S/N)_{\mathrm{coh}} \approx \frac{\eta I_{\mathrm{s}}}{e\Delta f} = \frac{\eta}{h\nu\Delta f} P_{\mathrm{s}}, \tag{12}$$

from which follows the minimum detectable power

$$(P_{\mathrm{min}})_{\mathrm{coh}} = \frac{h\nu\Delta f}{\eta}, \tag{13}$$

which is equal to the limit set by quantum fluctuations. It is not easy to reach this limit, however, even with coherent detection since the laser power required for it is very high and "burn out" phenomena of the photocell must be prevented. However, in the coherent case the quantum limit can at least be approached, which is virtually impossible using incoherent detection, at least for optical signals, since the factor

$$\sqrt{\frac{4kT}{M^2e^2R\Delta f}}$$

occurring in eq. (10) in practical cases greatly exceeds unity. For instance, with $R = 50\ \Omega$ and Af = $10^6$ Hz this factor amounts to about 30000, which gives the ratio between the minimum observable powers in incoherent and coherent detection, respectively. $(P_{\mathrm{min}})_{\mathrm{coh}}$ then turns out to be about $10^{-13}$ Win the near infrared or $10^{-19}$ W Hz-r. The laser power required to let laser induced shot noise dominate indeed all other noise is a few mW, which is still a feasible number for a stable gaslaser, the only type of laser coming into account here.

Another, not less important advantage of coherent detection is that the the phase of the incoming signal is retained in the photocell noise. Of course, this phase information usually disappears after further amplification, but in principle it can be retained. This makes it possible to use coherent detectors in stellar interferometric devices, thereby avoiding the difficult optical alignment and stability problems connected with the Michelson stellar interferometer, replacing them by much more simple electronic phase comparation methods. We come back to this later.

The principal difficulty of coherent detection is always local oscillator instability. The local oscillator now being a laser, such instability is certainly present. It seems feasible, however, to stabilize a laser within a bandwidth of a few MHz, and this corresponds to an optical resolving power of $10^8$ in the near infrared. Higher resolutions are not of interest, since they would exceed the resolution corresponding to the natural line width.

A fundamental difficulty of coherent optical detection is the narrow spectral range that can be covered. This is limited either by the response characteristic of the photocell (and then it is exceedingly small since photocells which are faster than a few times $10^{10}$ Hz do not exist), and this corresponds at wavelengths near $1\mu$ to a range of only $1$ Å, or by the possibilities

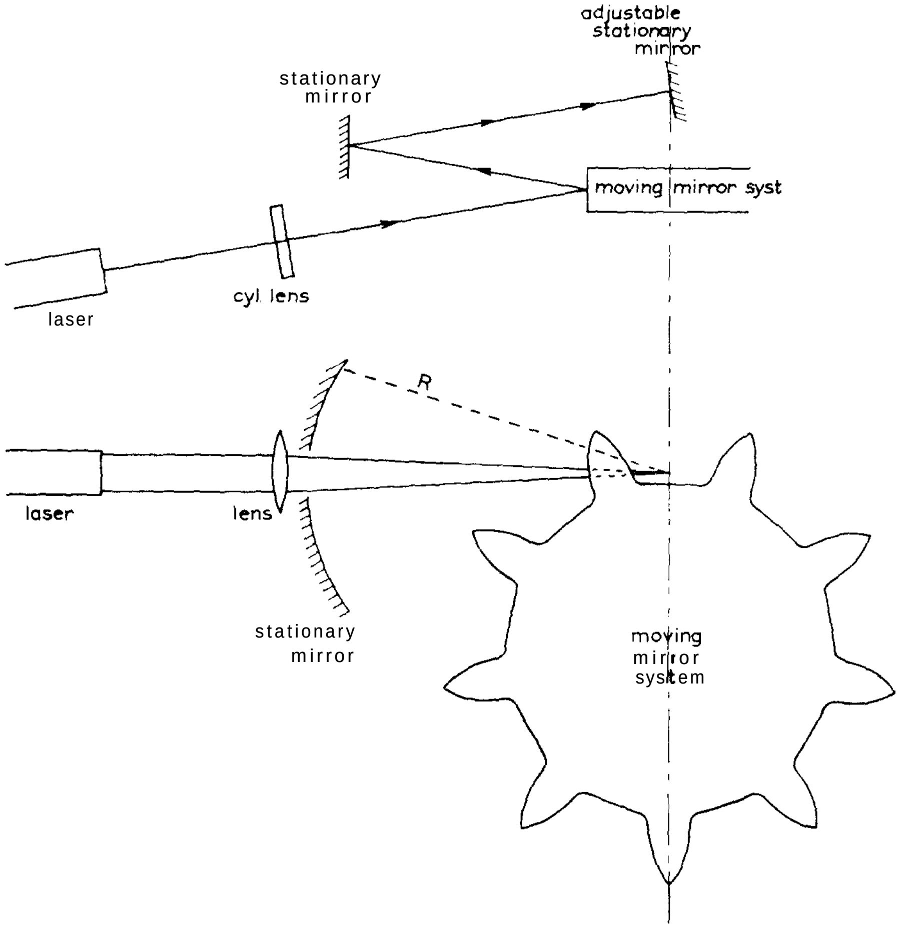


Fig. 2. Rapidly rotating "Dopplerwheel" as frequency shifter of a laser beam, seen from aside and from above.

to shift the frequency of a laser. At the time of writing, lasers with sufficient stability for coherent detection purposes (gaslasers in fact) can not be tuned in frequency by more than a few times $10^{10}$ Hz. A system which is now under development [4]) uses a rapidly rotating toothed wheel with reflecting teeth, so shaped that a parallel beam of light is reflected over 180°, apparently as against a fast moving mirror that remains parallel to itself (fig. 2). By using suitable materials and bearings, circumferential speeds of the order of 1000 m/s can be obtained and multiple reflections up to 50 times can be realized, which can produce together a wavelength shift of about 10 A. A spectral range of this order of magnitude seems thus obtainable. However, recent advances in laser materials and constructions make it probable that within a few years stable lasers which can be shifted in frequency over hundreds of ångström units will become available.

The transmission factor of a coherent optical detector can in principle be considerable. No lenses or windows are needed since the system is only sensitive for wavelengths near to the local oscillator wavelength. Only slight background filtering must be provided for, to ensure that the photocurrent due to background light remains sufficiently below the laser induced current. We expect that the transmission factor of such a system is of order $\tau \approx 0.5$. The only optical condition of importance that must be fulfilled is that the signal radiation and the laser radiation cover the same coherence area of the photodetector, in other words, that the incoming radiation is confined to the mode or modes in which the laser light vibrates. Spreading out of the light over a region larger than the coherence area would introduce statistical fluctuations between the beats received from different areas of the receiver and thus increase unwanted noise. This problem has been fully dealt with earlier 5). In practice it signifies that for the detection of spatially incoherent light, between the angular aperture $\alpha$ of the optical system and the effective diameter A of the photodetector the following relation must exist

$$A = 0.08\lambda^2/\alpha^2, \tag{14}$$

where $\lambda$ is the wavelength. Connes [6]) has shown how this condition disfavours coherent detection of extended incoherent light sources.

The acceptance of a coherent detector system is lower than that of an interferometric system by a factor $\sqrt{n}$, where $n$ is the number of modes present within the "étendue" of the optical system. In numbers, the acceptance of a coherent detecting system observing an incoherent extended source is given by

$$L = \tau\pi\alpha^2 A = 0.08\text{x}1\text{-}12 \tag{15}$$

and for radiation of 1 μm wavelength this is of order $10^{-9}$ cm$^2$. With a resolving power of $10^8$ an $LR$ product of 1 cm$^{-2}$ is reached. However, when a telescope is used as a light gathering instrument for a stellar source, the effective telescope area 0 should be considered as the receiver area, because the star image falls within the diffraction limits of even the biggest telescope, and spatial coherence (single mode reception) is assured. Thus, for such point sources the acceptance becomes

$$L = \tau\pi\alpha^2 O = 0.08\pi\tau\lambda^2 O/A. \tag{16}$$

Of course the transmission factor will now be somewhat smaller, but acceptancies of the order of $10^{-3}$ seem attainable with modest telescopes and with them $LR$ products of order $10^5$.

*Note:* Complementary to the spatial coherence condition discussed above there exists a temporal coherence condition, which involves the impossibility of observing lower difference frequencies than correspond to the natural linewidth : such frequencies have no time to build up.

For point sources (stars) the possibilities of coherent detection spectroscopy appear therefore comparable to or even better than those of Fourier transform spectroscopy. When tunable lasers will have been developed, coherent detection will surpass in many aspects the possibilities of interferometry, if only because of less optical complications and the much simpler way of data production. When no use is made of the extreme resolving power, the sensitivity of coherent detection systems may be one or more orders of magnitude greater than of interferometric systems. It appears, then, that for astronomical and space research applications, coherent detection spectroscopy may be of practical interest.

*Experiment*: Recently, a coherent detection system working in the laboratory has been demonstrated by Nieuwenhuijzen [7], a description of which has been given elsewhere. His system used a gas discharge as the (extended!) source. The predictions of the theory could all be verified in the experiment. A test on bright stars using a telescope is in progress.

3. *Applications of coherent detection in* astronomy. The following applications are under consideration :

1. Spectroscopy [8]. In the laboratory accurate line profile determinations in tenuous plasma may be used for the determination of *f* values of selected lines. Standard stellar (and solar) lines will be studied with a resolving power of 107 in bright stars of several spectral types. Doppler shifts of spectral lines can be determined with an accuracy of 0.1 km/s, again for selected lines.

Particular importance must be given to investigations in the near infrared spectrum, since there the sensitivity of coherent detection exceeds all other possibilities. In combination with space research exciting possibilities arise for the study of molecular interstellar lines, which would give more information about the composition of interstellar matter. By measuring from an orbiting satellite at various times of the year, use could be made of the Dopplershift produced by the revolution of the earth around the sun. This can not be done from the ground, since then one is looking always more or less in a direction opposite to that of the sun.

2. Polarimetry. Owing to the fact that coherent detectors are only sensitive to one polarization direction, *viz.* that of the laser signal, they can be used to study the distribution of polarization of selected lines over the solar surface, the interstellar gas, etc.

3. Stellar interferometry. Perhaps the most exciting application for coherent detection lies in the possibility for determining stellar diameters and even limb darkening as a function of frequency by interferometric means. This was suggested earlier by Gamo [9].

The signals from a star selected by two optical mirrors are converted into rf signals retaining their phase, by two coherent detectors using the same laser or two interlocked lasers. The rf signals are now compared in amplitude and phase by electronic means. This method opens the possibility of carrying out Michelson stellar interferometry with a baselength that may be one or more orders of magnitude greater than feasible with optical interferometers. The well known intensity fluctuation correlation method of Hanbury Brown and Twiss has the same advantage, but of course in this type of intensity interferometry all phase information is lost. In principle, coherent detection interferometry will yield exactly the same type of information as amplitude interferometry. Provisional studies as to this effect and its possible combination with radio interferometry have been carried out by A. D. Fokker and T. de Groot of this laboratory (unpublished). They concluded that the signal to noise ration to be expected from a coherent detection stellar interferometry system is exactly the same as that obtained by an intensity interferometer, *viz.*

$$\sqrt{BT} \cdot \eta N_s,$$

where $B$ is the rf bandwidth, $T$ the observing time, $\eta$ the efficiency of the photocell and $N_s$ the number of photons received per cycle and per second. Together with the additional presence of phase information, the outlook for a coherent detection interferometer therefore looks promising. It has to be realized however, that in phase sensitive high resolution interferometry, owing to the diurnal rotation and the consequent apparent rotation of the base line, measuring times are limited to about $3 \times 10^{12}/L\Delta\nu$ seconds, where $L$ is the baselength and Av the bandwidth. This limitation does not occur in phase insensitive interferometry. However, it seems possible to overcome it also in coherent detection by electronic means. A more serious complication may be that caused by unwanted phase fluctuateons due to atmospheric effects.

Acknowledgments. I am indebted to Mr. H. Nieuwenhuijzen for his strenuous efforts to realize the laboratory coherent detection system and his many new ideas on the subject, to Mr. H. J. van Amerongen, Mr. R. H. G. Helleman and many others for continuous help in its construction and to Dr. A. D. Fokker, Dr. T. de Groot and Mr. J. van Nieuwkoop for their help and advice, especially in the evalution of new possibilities of application.

This work is made possible by a grant from the Netherlands Organization for Pure Scientific Research (Z.W.O.) which we acknowledgw with pleasure.

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