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High Precision Wavelength Meter with Fabry-Perot Optics

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Abstract. A high precision wavelength meter in the visible is described, which is based on a Fabry-Perot interferometer with several etalons of different resolution. The interference fringe pattern projected on a photo-diode array detector is computationally processed to give a stepwise refinement of the wavelength value to any adjusted accuracy. The present model intends to provide digital and real-time values of high precision wavelength for dye-laser spectroscopy, and to serve as a monitor or as a pilot for wavelength control of a dye-laser source of nanosecond pulses. The model is, therefore, designed with particular emphasis on its short-pulse capability and on-line mode of operation as well as on its high sensitivity and resolution. Some arrangements of essential necessity are involved therein, such as to avoid an errorneous wavelength readout for a noisy incidence of pulsed field. The ultimate accuracy of wavelength measurement is prescribed by the resolving power of the thickest etalon employed. As applied to the pulsed source, the model determines the wavelength to the accuracy of $\pm$ one part in 10^7 for even a single shot nanosecond incidence of a fraction of μJ energy. The design and performance are described in connection to pulsed dye-laser incidence.

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There has been an increased necessity for a high-precision wavelength meter during recent development of dye-laser spectroscopy, and a variety of interferometric methods have been reported. The optical layout of these interferometer varies with each model depending on individual requirement as there are many trade-offs involved in the system design. Among the optical systems proposed thus far are Michelson-type moving carriage interferometers [1,3] and [Ref. 2, pp. 412, 421, and 425], Fizeau-type interferometers [Ref. 2, p. 419], polarization-sensitive interferometers with wavenumber readout [4] and [Ref. 2, p. 417], and Fabry-Perot type interferometers [5] and [Ref. 2, p. 514]. The first type successfully operates for high-precision purpose but exclusively with a cw source. The second type might be used for a pulsed source as well. However, it is not an easy task, to our experience, to keep up an accurate mode matching of incident light with the Fizeau type interferometer in a broad range of wavelength. The last type of interferometer employing several etalons of different resolution seems to be one of the most versatile version. It includes no moving part, and works either in cw or in pulsed regime. It determines wavelength to any adjusted accuracy.

The first success of this type of wavelength meter was reported by Byer et al. in 1977 [Ref. 2, p. 514]. They presented the successive method of wavelength determination through a set of etalons, such that an approximate wavelength value available from the lower resolution etalon was used to determine the order number integer of the next higher resolution etalon with which the closer value of wavelength was obtained. A monochromator-transmitted wavelength, known to within $\pm 4\,\mathrm{cm}^{-1}$, was determined to the accuracy of 10^{-7} by the use of three calibrated etalons of respectively 20, 2, and 0.2 GHz free spectral range.

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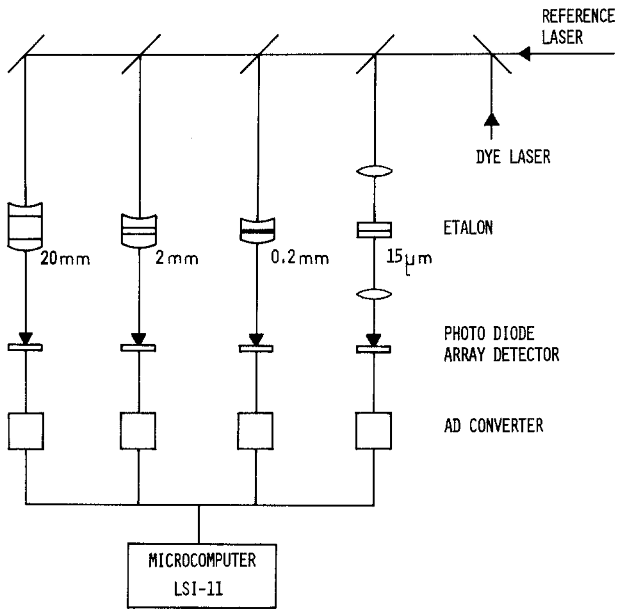

Fig. 1. Schematic of the optical layout of the Fabry-Perot interferometer system for wavelength measurement

An elaborate thermal stabilization and precise calibration of etalon constants required in their method were avoided in the method presented by Shimizu, in which a stabilized He–Ne laser was employed as a reference of wavelength measurement [5]. His recipé to evaluate the unknown wavelength λ against the reference wavelength λ_s is as follows: The interference fringe pattern produced by the concerned light is compared to that of the reference on a photo-diode array detector, and the fringe phase shift among the two is measured on each etalon as a fraction η of the reference fringe period. The fringe order number n for the concerned light as referred to the known order n_s for the reference light is determined uniquely to an integer from the relation

$$\lambda n = \lambda_s(n_s + \eta), \tag{1}$$

if a trial value of λ is available to within an accuracy of $|\Delta\lambda/\lambda| < (2n)^{-1}$. A closer approximation of λ is then obtained from (1) with substitution of the integer n thus obtained. A further improvement of the approximation is carried out in a way similar to Byer et al. [Ref. 2, p. 514] until the desired accuracy is attained. It was pointed out that the improvement of accuracy in the k-th step is limited to the extent

$$\left| \left(\frac{\Delta\lambda}{\lambda}\right)_k \Big/ \left(\frac{\Delta\lambda}{\lambda}\right)_{k-1} \right| \sim 2|\Delta\eta|_k, \tag{2}$$

where $|\Delta\eta|_k$ is the observational error of η on the k-th etalon, and that, in practice, the resolving power of each etalon is chosen in accordance of the dictates of (2). In his prototypical design, Shimizu employed four etalons of 10 THz to 7.5 GHz free spectral range, and demonstrated a measurement of cw dye-laser wavelength to the accuracy of 10^{-7} [5].

Our wavelength meter described here is definitely assigned for the task in our "on-line dye-laser spectrometer system" to give digital and real-time wavelength marks for spectroscopic measurement, and to make a pilot of wavelength control of the dye-laser source. The source radiation is a repetitive pulse of nanosecond duration, of several tens kW peak intensity, and of a spectral bandwidth of nearly transform-limited and of a few milliangstroms wide [6]. It is required, therefore, that our wavelength determination is of high precision to within an accuracy of at least ± 2 parts in 10^7 throughout the visible, of quick response enough to sample the nanosecond pulse incidence, is reliable and sensitive enough to work for a single shot of μJ energy, and is well specified for an on-line mode of operation. Our system design based on the Fabry-Perot interferometer is outlined in Sect. 1, in which the points of improvement to meet our specific application in the pulsed regime are described in some detail. The performance of the working model as well as its practical limit of utility is described in Sect. 2.

1. System Design

The schematic of the optical layout is shown in Fig. 1. The light beam to be measured is aligned colinear with the reference laser beam, is split into four beams of nearly equal intensity, and is directed to four etalons of different free spectral ranges. The interference fringe pattern is projected onto the photo-diode array detector (RETICON-CCPD) of 256 segments of 4 mm extension. The four etalons of respective spacings, 15 μm, 0.2 mm, 2 mm, and 20 mm, are all home-made. The mirror surfaces of the two thicker etalons are optically contacted to fused quartz spacers with the vacuum enclosed, while those of the other two are spaced by metal sheets. The fringe pattern projected on the photo-diode array is digitized by an AD converter, and loaded into a computer memory. The algorism of successive approximation of wavelength described in the preceeding section is executed by a built-in microprocessor. The design of the system is based on the prototype of Shimizu [5]. In our present version, however, the model is revised in many respects to achieve versatility to our specific application. The essential points of improvement are described in the following.

1.1. Protection from Incorrect Wavelength Determination

A point of prime importance in digital measurement is that an improper signal input which might lead to an incorrect result is removed automatically from the computational processing. It is to be noted that the light incidence of weak and fluctuated intensity apts to cause an erroneous wavelength readout. In Fig. 2, three typical interference fringe patterns as coupled out of the CCD photo-detectors [7] are shown along with their discriminated patterns. In case of a low noise incidence (Fig. 2a), the fringe positions, indicated by arrows, are determined to high precision by intensity discrimination of the photo-sensor output. In case of a low more noisy incidence (Fig. 2b), the fringe positions are given in less accuracy on account of a poor discrimination of the fringe slope. Such input signals are still acceptable to our wavelength calculation. For a very noisy incidence, on the other hand, the intensity discrimination gives an errorneous fringe pattern as shown in Fig. 2c, leading to an incorrect wavelength determination. Such an unacceptable input should carefully be removed particularly when the wavelength of an individual shot of repetitive pulse is concerned. In our present model, the above requirement is practically met with a simple arrangement such that the improper light incidence is distinguished by its count number of discriminated signals appearing in one fringe period.

1.2. Quick Initiation of Wavelength Calculation

It is a practical requirement of wavelength calculation that no long time is taken in the preliminary procedure such as to specify the optical adjustment of etalon relative to the photo-sensor, and to calibrate the nonlinear variation of the fringe period with etalon order number. We developed a computer program which executes these preliminary procedure directly after detecting two adjacent fringe period of the reference light. The obtained set of parameters characterising the condition of optical adjustment are stored in a non-volatile memory along with the program of wavelength calculation. The set of parameters are then readily loaded into the processor, or read out at need on a video terminal. This arrangement is of particular advantage in that the optical adjustment of the interferometer is promptly checked up, and that the initiation time of wavelength calculation is substantially avoided in practice.

1.3. On-Line Capability

A particular emphasis in our dye-laser spectrometer system [6] is given to the establishment of real-time spectroscopic data processing in close connection with the wavelength control in high precision. In order to meet this requirement, the wavelength meter is on-line controlled by the host minicomputer, DEC:PDP-11/34, and serves as a pilot of an automatic wavelength control. In local mode of operation the wavelength (or wavenumber by preference) calculated with a built-in microprocessor, LSI-11, is either displayed on an LED or sent to a wavelength marker. While in on-line mode of operation, the wavelength data are transferred to the host minicomputer through a full duplex serial line of 9600 bps by only a few macroscopic commands. The minimum essential commands are as follows: 1) read the wavelength of the next incidence to the cue, 2) inquire busy status, and 3)

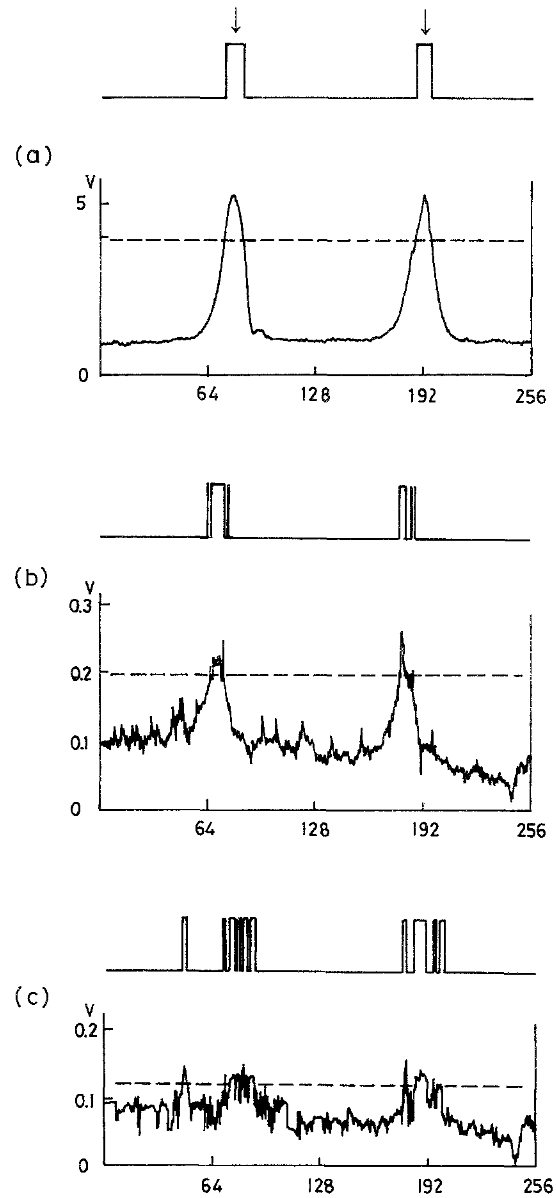

Fig. 2a–c. Interference fringe patterns displayed on photo-diode array of 256 segments. The CCD photo-detector output as sampled by the transient digitizer (Tektronix 7912 AD) after amplification is shown along with the discriminated fringe shape. The incidential energies are (a) 3 μJ, (b) 0.4 μJ, and (c) 0.2 μJ, respectively

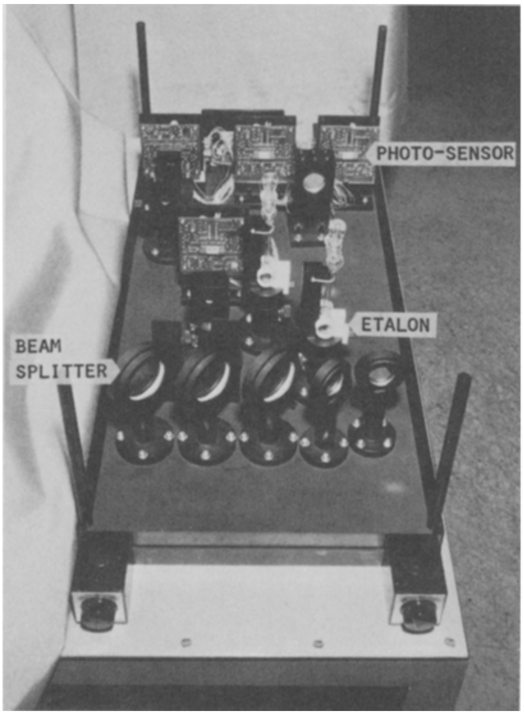

Fig. 3. Photographic close-up of interferometer optics

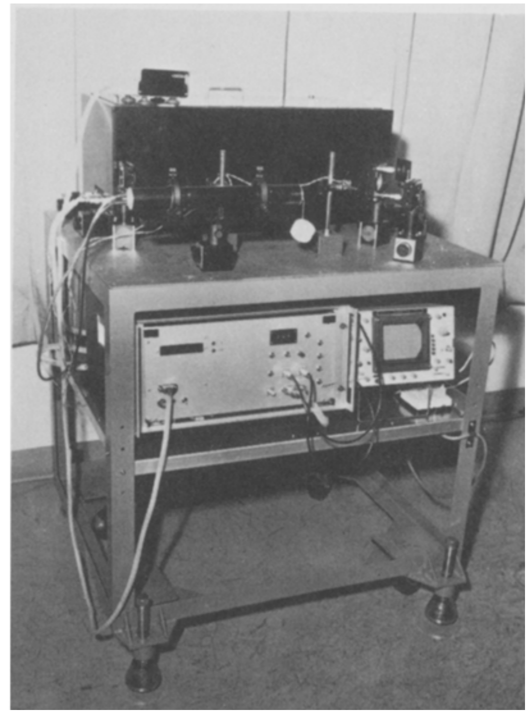

Fig. 4. Photographic picture of the working model of the wavelength meter

transfer the wavelength data to the host. The on-line capability offers a lot of versatility to various modes of spectroscopic application.

1.4. Broad-Band Capability

According to the recipé described in the Introduction, a trial value of wavelength, accurate to within $\pm 1\%$ for our specific model, is required in wavelength determination. Therefore the trial value must be revised for every, say, 4 nm. This is actually a troublesome task when the light source to be measured is extended over a broad range of wavelength. The present model is devised in this respect: it employs a digital switch and associated software by which the pertinent trial value is readily loaded at need into the processor. The model achieves thereby the conformity to broad-band operation.

The broad-band coating on etalon surfaces is an another point of care. We designed a seven-layered dielectric coating with ZnS and Na_3AlF_6, and achieved 85 % to 90 % reflectivity throughout the range of 450–650 nm wavelength. It should be noted that the coating is processed by one lot. This is important in that the dispersion effect on dielectric phase shift is made equal for each film, and that the effect can be canceled out in the computational procedure.

1.5. Self-Contained and Movable Setup

The interferometric optics, once properly adjusted, should remain in an optimum alignment for a reasonably long period of time. Each optical component is firmly mounted on a massive metal frame with minimum adjustability retained. A photographic close-up of the interferometer system is shown in Fig. 3. Since the light beam of a pulsed dye laser is unavoidably accompanied by directional instability, the wavelength meter is preferably placed close to the light source. The requirement is met with the model made to a compact and movable unit as represented photographically in Fig. 4. The incidential optics and the interferometric assembry are mounted on a common stage of 80 cm square together with the reference He–Ne laser. The latter part is shielded from optical disturbance. The digital processor and monitor oscilloscope of interference fringe pattern are set underneath. The incidential mode matching and path adjustment after locomotion of the stage is amply facilitated by this self-contained and movable setup.

2. System Performance

This section describes the performance of the working model along with the practical limit of its utility.

2.1. Optical Adjustment

The adjustment of the interferometric system is straightforward: Each etalon and associated condenser optics is adjusted so that a sharp and clear interference fringe pattern of the reference He–Ne laser is visible on the detector. In order to make best use of the available spacial resolution of the photo-diode array, etalons are preferably adjusted to image only one fringe period along the photosensitive extension of 4 mm length. Once the interferometric system is properly adjusted to the reference laser in this manner, the path adjustment for the incident beam is not too critical: The deviation from coincidence with the reference laser is, to our experience, plausible to the extent of 3 m rad.

2.2. Etalon Calibration

The calibration of etalon spacing, i.e. the determination of the fringe order number n_s for the reference He–Ne laser, should be carried out in at least two independent methods for confidence's sake. The method we adopted employs several auxiliary light sources of known wavelength. The known wavelength and the measured fractional fringe number of each auxiliary source is submitted, respectively, for λ and η in (1), and a unique and consistent integral number n_s is obtained. The multimode laser oscillations of 4 GHz bandwidth from Ar^+ laser (Spectral Physics SP-166) at 514.5, 510.7, 496.5, 488.0, 476.5, 472.7, 465.8, and 457.9 nm are conveniently employed as auxiliary sources to determine n_s for each of three low resolution etalons. The spacing of the thickest etalon are more carefully calibrated. The single-mode oscillations of a cw dye-laser (Coherent Radiation CR-599-21) of 5 MHz bandwidth are employed with its wavelength fixed on a certain Doppler-limited absorption line of iodine molecule[1]. The procedure mentioned above is repeated several times for different wavelengths of the cw laser in the range of 500 ~ 620 nm until the order number n_s for the thickest etalon is determined to a unique integer. The resulted integer number is examined with an alternative method described in [6].

2.3. Resolution

In order that the resolving power of each etalon is utilized to the full extent in the stepwise refinement, the fringe fraction measurement should meet the accuracy requirement expressed by (2). Since each etalon is assigned for a tenfold improvement of wavelength accuracy, the requirement of (2) is given by $|\Delta\eta| < 0.05$. If this is fulfilled, the ultimate accuracy available with

[1] The available data of the center frequency of iodine absorption spectrum is accurate to within ±30 MHz [8].

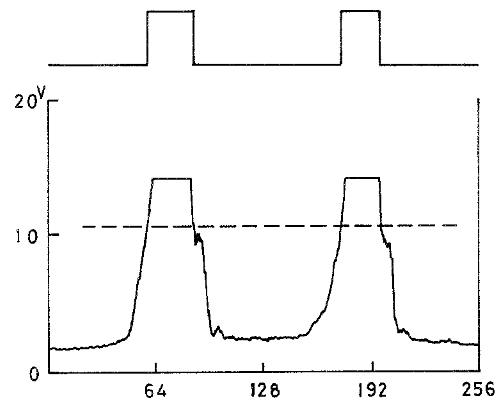

Fig. 5. Interference fringe pattern subjected to power saturation of detector. Incidential energy is 10 µJ. See the caption of Fig. 2 for signal treatment

the present method is prescribed by the resolving power of the thickest etalon. The spacial resolution of the photo-detection in cooperation to the subsequent digital processing allows one to determine the fringe phase to within an accuracy of 3 photo-sensing segments out of 200 segments extended over a fringe period. The effective finesse of 67 is thereby available, from which the ultimate resolution of ±60 MHz resulted from our thickest etalon of 7.5 GHz free spectral range.

In practice, however, limitation is apt to be imposed on the ultimate accuracy by frequency fluctuation of the reference laser, since interference fringes are all measured against the reference. On this account, the frequency stability of the reference laser must safely be one order of magnitude better than the prescribed resolution of the thickest etalon. A stabilized single-mode He–Ne laser (Tropel TM-100) with a frequency drift of well below ±10 MHz per day is satisfactorily employed as a reference in the present model.

2.4. Sensitivity

The sensitivity of the wavelength meter as applied for pulsed source is given in terms of the minimum energy involved in a single shot of measurable incidence. It is noted that the photo-sensor output is resolved to the extent of 80 mV with the A/D converter employed in the model, and that the figure is roughly twice the background noise on the photo-sensor output. Thus the tentative value of "sensitivity" is 0.4 µJ as limited by the resolution of the A/D converter. In practice, the incident energy as low as this limit is still useful for wavelength determination of prescribed accuracy owing to the arrangement described in Sect. 1.1.

2.5. Saturation Effect

On account of the power saturation effect involved in the charge coupling elements (photo-diode and/or

CCD), the finessé of the interference fringe falls off with an increase of incidence energy, and leads to the wavelength of poor accuracy. A typical fringe pattern exhibiting the power saturation is represented in Fig. 5. It should be noted that each photo-sensitive segment is saturated with an incidence of above 0.1 pJ. The practical upper limit of total incidence to be treated in our wavelength measurement of prescribed precision is at arround 10 μJ.

Conclusion

In conclusion, the present model proved to work successfully throughout the visible region with high precision (± 1 part in 10^{-7}), high sensitivity (0.4 μJ incidence in minimum), and quick response (40 Hz sampling). The model achieved a conformity to short pulse incidence by various arrangements, and operated with the prescribed precision for a single shot of nanosecond pulse incidence. Its versatility and utility was also pointed out to an on-line mode of operation for both wavelength measurement and spectroscopic device control.

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