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Development of Fast and Accurate Differential Wavelength Measurement Sensor

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***Abstract*— The Single longitudinal mode lasers with precise wavelength control have large number of applications. In most of these applications it is important to tune the laser to a desired wavelength value and then keep the wavelength fixed at that value. The desired target wavelength is attained to the required accuracy by adjusting the cavity parameters. Deviations from target wavelength are then constantly monitored to initiate corrective action, if necessary. The single line camera is used to capture the fringe pattern and digital signal processing hardware is used to process the image frame to calculate the differential wavelength of the different input laser beam. Differential wavelength measurement of the laser is useful for the feedback control of the wavelength. The image processing algorithm is developed to abstract data from the fringe pattern.**

I. INTRODUCTION

A Fabry-Perot etalon based sensor has been designed to detect variation in the wavelength of the single longitudinal mode Laser. The sensor works on the principle of detecting the variation in location of the fringe output of the etalon with time and relating it to the wavelength variation of the input laser.

The laser beam would be transported from laser room to control room through an optical fiber cable. The output of fiber optic cable would be connected to input of F-P etalon in the sensor. The output fringes of etalon are focused using a converging lens on a high resolution, high sensitivity, linear CCD array of size 2k X 1 pixels. The peak central location of the fringe width of a fully formed fringe is calculated using quadratic fit algorithm in the Digital signal processing (DSP) circuit attached to the output of the camera carrying linear CCD array. The pixel value of this peak is constantly monitored and compared with the previous reading. Any deviation in this value results in generation of an error signal which is sent to the control unit for determining the corrective action. Since it is required to detect the variation at a fast rate, the line scan camera carrying linear CCD array would be operated at the frame rate of 10 k frames per second and within the 100 μsec time between two frames, the error data is generated by the dedicated high speed DSP card connected to the camera. The output of DSP card would be connected to the main control CPU card through an Ethernet interface.Many scientific, military, medical and commercial laser applications have been developed since the invention of the laser in 1958. The coherency, high monochromaticity, and ability to reach extremely high powers are all properties which allow for these specialized applications. The laser is popular in spectroscopy application, laser range finding, photochemistry, laser cooling, nuclear fusion, microscopy and etc.

The wavelength meter is commercially available, which uses interferometric measurement techniques such as Fizeau interferometer,Michelson and Fabry- Perot interferometer. The absolute measurement of the wavelength takes few hundreds of the millisecond time as it has multiple interferometers. The wavelength feedback control mechanism requires fast measurement system, which could read the wavelength change and gives data for the feedback control.

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II. SYSTEM OVERVIEW

The proposed system includes the sensor, where FP interferometer is used to generate the fringe pattern of the laser as shown in the Fig 1

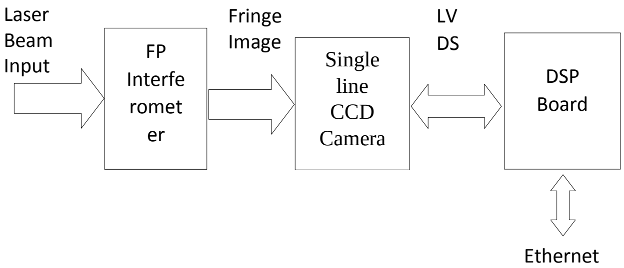

Fig 1. Scheme of measurement

The laser input can be directly coupled to the interferometer and also could be through fiber optics. The camera output data can be sent to a DSP based card in LVDS format at the maximum rate of 10 K fps. If the threshold value is set in the FPGA of camera then only intensity values of those pixels, whose value are higher than the threshold, will be sent to the DSP card. This will reduce the amount of data to be handled by DSP and will improve the speed of response. The DSP based card will have serial and Ethernet output. There will be custom programming of DSP in C language and it can be reprogrammed for testing during the development phase.

The video port is programmed to read and save images into the memory in FIFO manner. The DSP board processed the image to derive the differential wavelength change. The processing time of the DSP image is optimize to less than 1 msec. Thus, the sensor in all can respond within 2 ms, the measurement rate could be 500 Hz. The DSP, DM 642 series of Texas Instrument is selected, which has dedicated video port and can be clock to 720 MHz speed. The single line CCD sensor of 2048 pixels is used.

III. PRINCIPLE OF OPERATION

A Fabry–Pérot interferometer or etalon is typically made of a transparent plate with two reflecting surfaces, or two parallel highly reflecting mirrors. Its transmission spectrum as a function of wavelength exhibits peaks of large transmission corresponding to resonances of the etalon. It is named after Charles Fabry and Alfred Perot. "Etalon" is from the French etalon, meaning "measuring gauge"

The path difference between parallel output rays is in multiple of wavelength of incidence ray (λ) then they will interfere at the meeting point to cause constructive interference i.e. a bright spot, and if the path difference is multiple of λ/2 then it will be destructive interference resulting in dark spot.

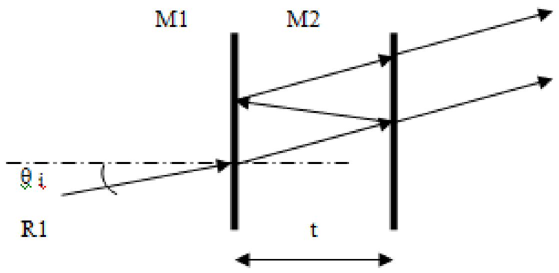

Fig2. Schematic of F-P etalon

Any ray R1 entering the etalon at an angle θ_i undergoes multiple reflections inside etalon with multiple output rays, each parallel to each other and parallel to incident ray. If the mirrors are exactly parallel to each other (which is expected in ideal case) the output parallel rays will meet at infinite to form fringes. However if the mirrors are not exactly parallel, the output rays will meet at a finite distance to form fringes. If a focusing lens is used at the output of the etalon then

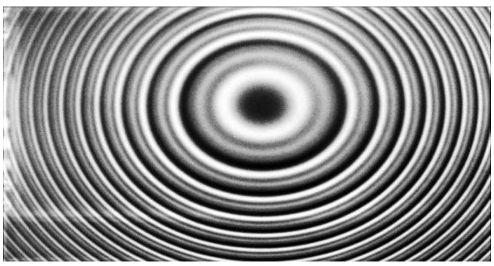

Fig 3.Fabry Perot Etalon Rings Fringes

parallel output rays will meet at the focal plane of the lens to form fringes.

Proper design of an etalon based locking system does require attention to a few key parameters andconcepts. The choice of material type and thickness for the etalon determines both the peak

The transmission frequencies and the free spectral range, or frequency spacing between peaks. These parameters are not independent and must be chosen based on the application. Second, the dispersion of

the chosen material must be factored into the expected performance of the etalon.

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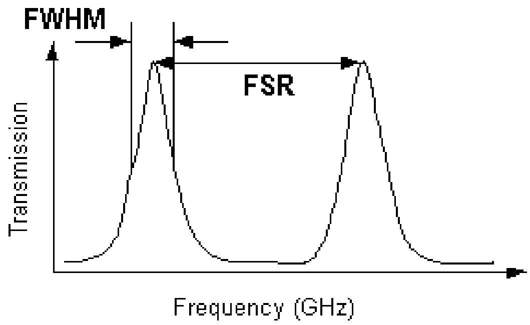

Fig.4. Transmission Vs Frequency

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IV. CALCULATION CONSIDERATION

A.Step-1

For 20 mm effective aperture of etalon, we take diameter of cylindrical lens as 25 mm. So with this diameter and desired angle of 0.996 degree, the focal length of the lens should be

$$\tan\theta = D/2f \quad (1) \quad \text{Or } f = D/2\tan\theta$$

Now θ=0.996°, D=25 mm, so f = 719 mm

Since we want angle to be equal to or more than 0.996, so **f** should be less than or equal to 719. To make it a round figure, we should keep the f=700 mm.

Thus focal length of cylindrical lens = 700 mm

The cylindrical lens is to be oriented so that it converge the collimated beams in horizontal direction and all the beams should make 0 degree in vertical direction. This way after the beams are passed through the etalon, they will be focused in a horizontal strip. Thus all the intensity of a fringe is focused to a small area. As we intend to use a linear CCD array in a line scan camera for detection offringes, this will be helpful in detection of fringes with less intensity of input laser beam also.

B.Step-2

Calculations to find the fringe diameters and fringe width are given below. These calculations can identify the focal length required to be used on the imaging side of FP etalon with a given sensor size.

The FP etalon equation is

$$2\mu t\cos(\theta) = n\lambda \quad (2)$$

μ is the refractive index of the medium between the parallel plates. The thickness (gap between the plates) of the etalon is given as t, θ is the angle of the fringe from the optic axis, n is the order, and λ is the wavelength of the source. The maximum order of the fringe occurs at the center of the fringe, where θ is zero.

$$2\mu t = (n_{\max} + \varepsilon)\lambda \qquad (3)$$

$$m_p = n_{\max} - (p-1) \qquad (4)$$

m_p is the number of the fringe from the center. Substituting in FP equation and rearranging the terms we get

$$2\mu t(1-\cos(\theta_p)) = (p-1+\varepsilon)\lambda \quad (5)$$

$$4\mu t Sin^2(\frac{\theta_p}{2}) = (p-1+\varepsilon)\lambda \qquad (6)$$

where θ_p is the angle of the m_p^{th} fringe

For small angle and using refraction equation, the fringe angles for bright fringes,

$$\theta_p = \frac{1}{n}\sqrt{\frac{n'\lambda}{t}}\sqrt{(p-1+\varepsilon)} \quad (7)$$

n and n' are the refractive indices of outside and inside the FP plates. ε is the fractional order of the FP fringes.

C. Step-3

The FP fringes are also called fringes of equal inclination. The fringes are focused by spherical focal length of F. Diameter of the fringe at the focal plane for p^{th} fringe is

$$D_p = 2*F*\theta_p \qquad (8)$$

If θ_p=0.996 (angle required for 18 fringes), D_p=14 mm (size of sensor), then

$$F= 14/(2*0.017)=402mm \qquad (9)$$

Thus we have taken focal length of focusing lens =400 mm

$$D_p^{\ 2} = (2F\theta_p)^2 = \left(\frac{4n'\lambda F^2}{n^2 t}\right)*(p-1+\varepsilon) \quad (10)$$

For air spaced etalon n=n'=1

$$D_p^{\ 2} = \left(\frac{4\lambda F^2}{t}\right)*(p-1+\varepsilon) \qquad (11)$$

p=1 is the first central fringe. Diameter of each fringe from the center is evaluated.

D_{p+1}-D_p= 2* FSR (In equivalent spatial domain)

FSR is the free spectral range [11] [12] where each spatial point is unambiguously representing each wavelength within the range of the wavelength spectrum.

V. CCD SINGLE LINE CAMERA

CCD line-scan cameras are used in measurements e.g.for dimension measurement applications where the resolution (number of pixels) of cameras with area CCD sensors is not sufficient and the whole image of the measured object is not required. Although the camera is designed as a stand-alone device, it has interfaces to communicate with PC as well as with manufacturing process.The parallel interface working in the EPP (Enhanced Parallel Port) mode can be used for quick transmission of the whole image into a PC. E.g. algorithms can be then debugged and tested in the PC first and then implemented into the DSP. The serial interface (RS232) is suitable for transmission of small amounts of data such as results of measurement.

A line scan camera of size 2k x 1 pixels with pixel size7 μm x 7 μm would be used as high resolution detector.The DSP module will receive data from the camera in LVDS format at the max. rate of 100 Mbps.

VI. FOCUSING OF FRINGES

In design of F-P sensor, we are using a focusing lens of focal length 400mm at the output of etalon. Our sensor is a linear CCD array of length 14 mm placed at the focal plane of the focusing lens. So for CCD to capture 18 complete circular fringes, it should subtend an angle to the center of focusing lens which should be equal to or greater than 0.996 degree. In this case, the maximum angle subtended (θ_{max}) is $\tan^{-1}$(7/400) or 1.002°, which is greater than 0.996 degree. So the sensor will capture all 18 fringes.

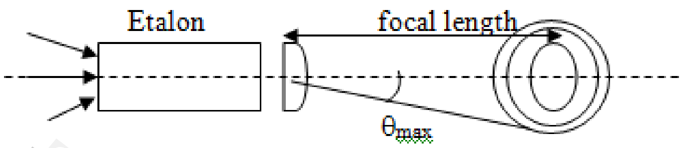

Fig 5 Fringe focused at output of etalon

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It is required to focus the output of etalon in a narrow arc along horizontal line. So to achieve this we will first collimate the beam coming out of the fiber using a plano-convex spherical lens and then use a cylindrical lens of long focal length to converge the beam in only one direction, so that the convergence angle is about 0.996 degree for formation of 18 fringes.

VII. SOFTWARE DESIGN

The fig 6. represents the flow diagram of the software.

In Image Processing Image registration is often used as a preliminary step in other image processingSet pixel value is zero. If pixel value is greater than threshold band read pixel value is equal to pixel intensity.If threshold value is less than pixel value again read pixel value. The processor takes the intensity values of the linear array of pixels as input.

This array comprises a number of groups of contiguous pixels whose intensity values exceed a pre-specified threshold, henceforth referred to as band. Each fringe results in two such bands symmetrically placed from center of the fringe pattern.The algorithm has been developed to monitor the fringe location on the CCD sensor by finding the peak of the intensity pattern along the fringe width **using** quadratic fit fitting.

Set Pixel = 0
Read PI = Pixel Intensity
Is Pixel > Threshold Band Location
Pixel = Pixel + 1
Peak determination
Compute

$a = -(\sum x^2y(\sum x)^2 - \sum x\sum x^2\sum xy - \sum x\sum x^3\sum y + (\sum x^2)^2\sum y + N\sum x^3\sum xy - N\sum x^2\sum x^2y)$

$b = \sum x \sum x^2\sum x^2y - \sum xy(\sum x^2)^2 + \sum x^2\sum x^3\sum y - \sum x\sum x^4\sum y - N\sum x^3\sum x^2y + N\sum x^4\sum xy)$

$peak = -b/(2 * a)$

A. Timing Considerations

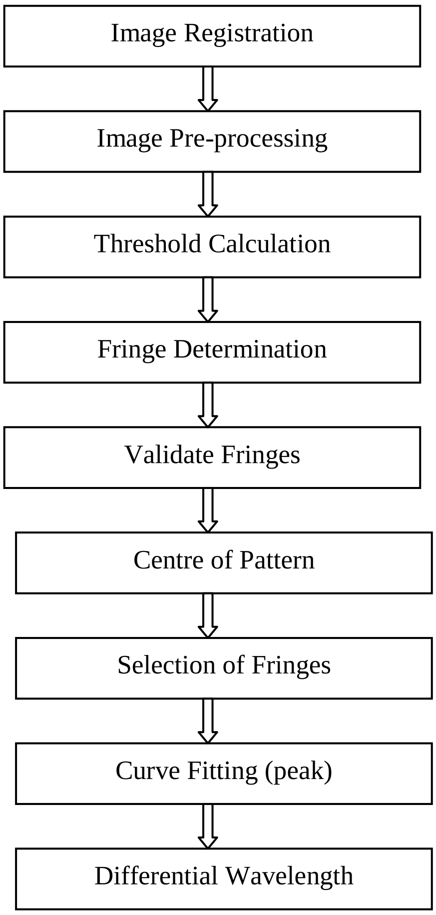
Following timing for algorithm is done for 720MHz DM640 DSP chip. Salient features of DSP pertaining to the calculations are as under:

1. 8 instructions can be executed per cycle
2. There are six ALUs – each supporting single 32 bit or dual 16 bit operation per clock cycle
3. There are two multipliers – each supporting two 16 bit * 16 bit (32 bit result) per clock cycle or four 8 bit * 8 bit (16 bit result) per clock cycle
4. All instructions can be conditional
5. Read operations can take up to 24 cycles in the worst case

Based on the analysis of algorithm, the DSP DM642 of Texas Instruments is suitable for the application.

The output will be available within 1 ms of available time between two frames for frame rate of 1 k frames per second.

Fig 6. Flowchart



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VIII. IMAGES

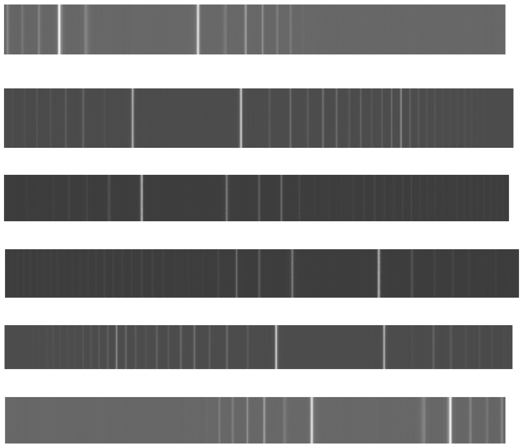

Fig 7. Line fringes obtained by F P etalon of pulsed laser

IX. EXPERIMENTAL RESULTS AND ANALYSIS

Image	Mean	Fringe	Center	Delta	Wavelength
im_20_5_1.bmp	111.918	11	554.5000	12.1482	0.6264
im_50_2_1.bmp	82.78	23	734	12.3775	0.6382
'im_50_2_3.bmp	66.1397	20	723.5000	12.1934	0.6287
im_20_5_3.bmp	82.5701	25	1311	12.3967	0.6392
im_20_5_4.bmp	66.72	21	365	3.729	0.193
im_20_5_2.bmp	111.41	11	570	12.97	0.669

X. CONCLUSION

FP Sensor will be used to detect the position of locking fringe in the wavelength stabilization loop of the Laser control system.

This position information will be used to keep the wavelength at its set point value.

The parameters like the differential wavelength and linewidth of the input laser light can be determined from the measurement of parameters: fringe diameters, fringe width and inter-fringe spacing.

Laser results in the shift in the location of output fringes. This shift is detected by the high resolution detector to generate error signal for wavelength feedback system. The sensor has utility in many applications. It gives fast and very accurate readings. The choice of CCD camera and DSP board and software development are the key components to make sensor very rugged and areliable.

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