dB, the measured and simulated ones are −21 dB in the $E$-plane and −15 dB in the $H$-plane, respectively, due to an imperfect power distribution and element spacing of 24 mm along the vertical center feed line.

The gain is 30 dB, and the 3 dB beamwidth is 4.6 and 4.1° in the $E$-/ $H$-plane, respectively. The gain and beamwidth of the 20 × 20 array antenna are summarized in Table 1.

### 4. CONCLUSION

A microstrip single patch antenna with parasitic patches was developed, and yielded a bandwidth of 15%. A parallel-series feed network with minimum feed lengths was utilized to combine element antennas. A series feed network was designed from the Dolph–Chebyshev method for a −30 dB sidelobe level, while the simulated and measured SLL shows −15 dB due to the feed network. The array antenna provides a gain of 26.0−30.7 dB, and the 3 dB beamwidth is 4.5–5.1° in the $H$-plane and 4.1–7.1° in the $E$-plane, respectively, at 24.2–26.7 GHz for LMDS applications.

### REFERENCES


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### IMPROVED TUNING ACCURACY OF FIBER GRATING LASERS USING A LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

W. H. Chung,† H. Y. Tam,† M. S. Demokan,§ and P. K. A. Wai†

† Department of Electrical Engineering
Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong SAR, P.R. China
§ Department of Electronic and Information Engineering
Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong SAR, P.R. China

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ABSTRACT: A microprocessor-controlled feedback system using a linear variable differential transformer to measure the compression of a fiber Bragg grating with a view to improve the tuning accuracy of a fiber Bragg grating laser is reported. This technique overcomes the large hysteresis of the PZT actuator normally used to compress the grating. A tuning range of about 20 nm with a readout wavelength accuracy of better than ±0.05 nm was achieved. © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 32, 37–40, 2002.

Key words: fiber lasers; wavelength tuning; fiber Bragg gratings; WDM applications
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INTRODUCTION

Fiber lasers based on fiber Bragg gratings (FBGs) are promising candidates for dense wavelength-division multiplexing (DWDM) systems because of the ease of producing an FBG with a highly accurate and repeatable Bragg wavelength that matches the ITU wavelength grids. Recently, there has been intense interest in employing tunable sources in DWDM systems to use as “spare” components in order to reduce cost by stocking fewer spare lasers. Tunable fiber grating lasers offer an important advantage in this respect because an FBG can be tuned over a large wavelength range in comparison with a semiconductor laser which normally can be tuned over just 1–2 nm.

FBG tuning is generally achieved by using either thermal or mechanical methods [1–5]. The direct thermal tuning technique provides a limited tuning range because of the small wavelength temperature coefficient of an FBG (the typical value is $\sim 0.012 \text{ nm/}^\circ\text{C}$), and it is also a very slow tuning technique. Mechanically stretching or compressing an FBG enables a wider tuning range of more than 44 nm [5].

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Most mechanical techniques employ a PZT actuator to compress/stretch the grating to achieve a large tuning range [2–4]. The main issue in using PZT actuators is their large hysteresis [6]. Therefore, their elongation cannot be determined with any accuracy from the applied voltage. Sensors have been employed to measure a PZT's elongation in order to overcome the hysteresis problem. In [5], strain gauges were epoxied onto PZT's to determine an FBG's compression/elongation when voltage was applied to the actuators that compressed the FBG; a tuning accuracy of 0.3 nm was demonstrated. In this letter, we report the performance of a new kind of tunable fiber laser that uses a linear variable differential transformer (LVDT) [7] to determine the laser wavelength with an accuracy of better than ±0.05 nm. This is a factor of 3 better than that reported in [5]. Our preliminary results demonstrate that a high scanning rate of greater than 500 nm/s can be achieved with this technique. This kind of laser may find applications in DWDM systems as well as in DWDM component characterization where tunable lasers are used. At present, the scanning rate of a semiconductor tunable laser is quite slow, and has a typical scan rate of about 10 nm/s.

**PRINCIPLES OF OPERATION**

The configuration of the tunable grating laser is shown in Figure 1(a). It consists of an erbium-doped fiber amplifier, with one of its inputs connected to a broadband mirror and the other input connected to a tunable FBG 1 cm long. The FBG was fabricated in hydrogenated SMF-28 fiber using the phase mask technique. The Bragg wavelength of the grating is 1561.45 nm, and its reflectivity is about 96%. An optical isolator was inserted after the grating to prevent any unwanted reflections back to the laser. The spectrum of the laser output was measured with an optical spectrum analyzer, which has a resolution of better than 15 pm and a wavelength accuracy of 0.1 nm.

Figure 1(b) shows the mechanical and electronic setup for tuning the grating. The grating was kept straight by inserting it inside two ceramic ferrules that have an inner diameter of 128 μm. Both ends of the fiber incorporating the grating (but not the grating itself) were epoxied to the ferrules which are separated with a gap of about 1 mm to allow for compression. A sleeve ring was employed to secure the ferrules. The ferrules were fixed onto two metallic assemblies, which themselves were mounted onto two translation stages. One of the translation stages was fixed; the other could be moved by a motorized actuator to compress the grating. The amount of compression that the grating experienced was measured with the LVDT that was connected to the stages, as shown in the figure. The miniature dc-energized LVDT has a sensitivity of 750 mV/mm and a nonlinearity of 0.05%. The output voltage of the LVDT is proportional to the position of the core inside the armature, and therefore proportional to the compression that the actuator induced on the grating.

The fractional change in the laser wavelength as a result of the compression applied to the grating $\frac{\Delta \lambda_L}{\lambda_L}$ can be written as [2]

$$\frac{\Delta \lambda_L}{\lambda_L} = C(1 - \rho_e)x$$  (1)

**Figure 1** Configuration of the tunable fiber laser. (a) Optical setup. (b) Mechanical and electronic setup
where $\rho_c$ is the photelastic constant ($\rho_c = 0.21$ for silica fiber), $x$ is the armature position, and $C$ is a constant which depends on the LVDT sensitivity, grating, and compression lengths. Therefore, the laser wavelength is proportional to $x$, which can be determined by the LVDT output voltage. The output voltage is amplified and then digitized using a 12 bit A/D converter before being fed to the microcontroller (AT89C52).

EXPERIMENT AND RESULTS
The experimental setup is shown in Figure 1(a) and (b). The actuator was used to calibrate the LVDT, as well as to determine the relationship between the laser wavelength and the LVDT output [i.e., to obtain the constant $C$ of Eq. (1)]. The results are shown in Figure 2. Both relationships show very good linearity, with slopes of 17 mV/\mu m and 55.4 pm/\mu m over the travel range of 360 \mu m. The value of $C$ is calculated to be 44.2 m\(^{-1}\). Note that the combined hysteresis and backlash of the actuator introduced an error of about 1.3 nm in the laser wavelength. Figure 2 also shows how the LVDT improves the wavelength accuracy of the laser to about 0.1 nm despite the actuator backlash and hysteresis. These values were used in the program of the microcontroller to calculate the laser wavelength. The microcontroller was programmed to receive the input voltage via the keypad. It controls the actuator until the LVDT output voltage reaches a value that corresponds to the input wavelength. The LCD display shows the value of the wavelength calculated from the output voltage of the LVDT. The spectra of the laser output are shown in Figure 3. The total tuning range of the laser is about 20 nm. Tuning repeatability and accuracy of the laser are very good. Several test cycles of the fiber laser were conducted by entering, via the keypad, a series of wavelengths with decreasing values, and then with increasing values. The differences between the LCD display readouts and the OSA measurements are shown in Figure 4. It is seen that an accuracy of better than $\pm 0.05$ nm can be achieved. The technique presented here does not depend on the actuator's hysteresis because it measures the compression directly. It also offers a number of advantages when compared with strain gauges. Our system is simple to install, able to measure much larger travel, and a more direct technique. We believe that the tuning accuracy could be improved by using an actuator with a better repeatability to calibrate the LVDT and to reduce the noise of the LVDT.

CONCLUSION
In conclusion, an LVDT displacement sensor was applied successfully to measure the compression applied to a fiber grating laser so that its lasing wavelength can be determined. The laser wavelength was tuned with an actuator. The hysteresis of the actuator was overcome by the LVDT, which measures the compression directly. A microcontroller was employed in the laser prototype to attain a compact, cost-effective, and programmable tunable fiber laser which has potential application in DWDM systems as well as in component characterization. Repeatable tuning over a range of 20 nm was achieved with a wavelength accuracy of better than $\pm 0.05$ nm.

REFERENCES
ON THE EVALUATION OF THE TRUE PHASE OF INTERFEROMETERS

Falih H. Ahmad,1 Gary L. Heims,1 Ray M. Castellane,2 and Bartley P. Durst†
1Department of Engineering Technology
University of North Carolina—Charlotte
Charlotte, North Carolina 28223
2Waterways Experiment Station
Engineer Research and Development Center
Department of the Army
Vicksburg, Mississippi 39180-6199

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ABSTRACT: An iterative technique that uses sine and cosine modulations along with low-pass filtering to extract the true phase values of a carrier frequency interferogram is proposed in this paper. An illustrative example is given in which this technique is applied. Results generated from the application of this technique are compared with exact phase values, and excellent agreement between the exact and computed phase values is demonstrated. © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 32: 40–43, 2002.

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1. INTRODUCTION

The phase of an interferogram is related to the physical quantity being measured, such as depth measurement, strain analysis, temperature gradients, and surface deformation [1]. True phase values of interferograms are vital in many fields of research [2], and their evaluation has been extensively studied for applications in automated manufacturing, robotic vision, and quality control [3], computation of real imagery [4], optics [5], signal processing [6], magnetic resonance imaging [5, 6], synthetic aperture radar (SAR) interferometry [4], [5, 7, 8], solid-state physics [6, 9], and optical metrology [10]. Notably, in many interferogram phase-evaluation techniques, only the wrapped phase values, which are the principal phase values, are measured or directly computed [4], and accordingly, phase unwrapping has been under considerable study over the past two decades [11]. Computations that produce wrapped phase values experience the phase modulo 2π effect, where resulting phase values lie between −π and +π [12, 13]. As an example, a synchronous method is used in [14] to develop an iterative algorithm to obtain the wrapped phase, where the wrapping operator is a trigonometric function. Given the wrapped phase values, phase unwrapping is the task of finding the true phase values [4]. Phase unwrapping is a demand common from many fields of research mentioned above, where the true continuous phase is obtained by removing the 2π discontinuities from the wrapped phase [15, 16]. In general, phase unwrapping consists of two steps: the first step is the estimation of phase gradients from the interferogram, and the second step is the integration of the gradient estimates to obtain the unwrapped phase values [7]. Numerous algorithms exist to find the unwrapped phase; however, no single algorithm can do everything well [17]. Two criteria are usually considered for the selection of an optimum technique for phase unwrapping: these criteria are the wrapped phase map and the available time [17]. Examples of techniques used for phase unwrapping are the block least squares method [4], the regularized phase-tracking system [1, 10], the frequency-based analysis method [11], the branch-cut method [12], and the quad-tree decomposition method [15]. The technique proposed here seeks to obtain the true phase of a carrier frequency interferogram without the need for unwrapping.

The sections of the paper are organized as follows. The technique for the evaluation of the true phase values of an interferogram is developed in Section 2. This technique is utilized in Section 3, where its performance is demonstrated through the solution of an illustrative example.

2. EVALUATION OF TRUE PHASE VALUES

2.1. First Estimation of the Unknown Phase. The irradiance of a carrier frequency interferogram with a linear spatial frequency ω0 can be presented as [3, 14, 18]

\[ I(x) = a(x) + b(x) \cos(ω₀x + φ(x)) \]  

(1)

where \( x \) is an integer value representing pixel position, \( a(x) \) is the background intensity, \( b(x) \) is an amplitude-modulating term, and \( φ(x) \) is the unknown phase. The assumptions under which Eq. (1) is considered are [14]

\[ ω₀ > \frac{∂a(x)}{∂x} \]  

(2)

\[ ω₀ > \frac{∂b(x)}{∂x} \]  

(3)

\[ ω₀ > \frac{∂φ(x)}{∂x} \]  

(4)

For clarity purposes, the dependence of the functions \( a(x) \), \( b(x) \), \( φ(x) \), and \( I(x) \) on \( x \) hereafter will be implicit. To start the proposed iterative technique, we generate the first estimation of the unknown phase. This is accomplished through the application of the sine and cosine modulations to develop two signals [14]:

\[ I_π = I * \sin(ω₀x) = a \sin(ω₀x) + \frac{b}{2} \sin[2ω₀x + φ] - \frac{b}{2} \sin[φ] \]  

(5)

and

\[ I_π = I * \cos(ω₀x) = a \cos(ω₀x) + \frac{b}{2} \cos[2ω₀x + φ] + \frac{b}{2} \cos[φ] \]  

(6)

where the asterisk denotes multiplication operation. In addition, the signals given by Eqs. (5) and (6) are low-pass filtered.