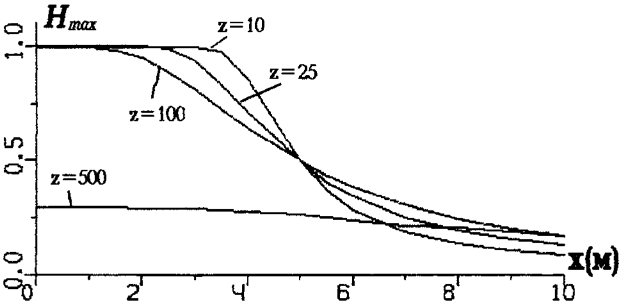

Figure 5 Distribution of the radiated pulse amplitude over the height x, in the plane $y = 0$, versus z for a square aperture, $a = 10$ m

delay $\Delta\tau$ does not change with increasing height x up to the vertical dimensions of the aperture $x = a/2 = 5$ m. The time delay $\Delta\tau_1$ is the difference of the arrival times into the observation point M between the main pulse and the pulse scattered by the upper horizontal aperture boundary. The time delay $\Delta\tau_1$ decreases with the growth of the vertical x coordinate. It is clearly shown by the results of the numerical calculations (Figure 4). Finally, the time delay $\Delta\tau_2$ is the difference between arrival times of the main pulse and the pulse scattered by the lower horizontal boundary of the aperture. The time delay $\Delta\tau_2$ increases with the growth of the vertical x coordinate. The temporal delays $\Delta\tau$, $\Delta\tau_1$, and $\Delta\tau_2$ decrease with the growth of the distance z from the aperture plane.

Figure 5 shows the dependences of the pulse amplitude on the height in the plane $y = 0$ for different values of the longitudinal coordinate. The calculations are performed for the case of a square aperture with sides $a = 10$ m. It follows from these curves that when the aperture is getting more distant from the plane (increasing z), the distribution of the pulse amplitude in the cross section smooths. For short distances in the paraxial area the amplitude of the pulse is almost unchanged with the growth of z.

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FULLY AUTOMATIC SIMULTANEOUS FIBER GRATING AMPLITUDE AND GROUP DELAY CHARACTERIZATION

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ABSTRACT: *We present a novel fiber grating measurement technique based on the direct modulation of a tunable laser source by an optical component analizer (COA). © 1997 John Wiley & Sons, Inc.* Microwave Opt Technol Lett 14: 373–375, 1997.

Key words: *optical fiber; group delay; fiber grating; tunable laser*

I. INTRODUCTION

Fiber Bragg gratings are finding increasing applications in telecommunications and sensing [1, 2]. The development of chirped fiber gratings in particular allows for the implementation of dispersion compensators with outstanding performance [3]. In this last application, there is a strict requirement for accurate amplitude and phase characterization of the fiber grating. Several techniques have been developed so far to accomplish this requirement, including those based on an rf-modulated Michelson interferometer [4, 5] and those employing low coherence interferometry [6]. These techniques rely on the use of optical interferometers, and hence require signal path control and stabilization loops against environmental variations.

In this Letter a novel fiber grating measurement technique is presented that is not based on optical interferometry but on the direct modulation of a tunable laser source by an optical component analyzer (OCA). The measurement technique is robust, yields repeatable results, and does not require a special stabilization scheme. Furthermore, it has been developed to be fully automatic.

II. MEASUREMENT TECHNIQUE DESCRIPTION

The basic configuration of the measurement system is shown in the upper part of Figure 1. An rf sinusoidal current $i_e = I_e[1 + m \cos w_e t]$, where $m \ll 1$ represents the modulation index and w_e the rf carrier frequency, directly modulates a low-linewidth tunable external cavity laser. The electric field from the optical source $E_l(t) = \sqrt{C_L I_e \cos w_e t} \cos w_o t$, where C_L and w_o represent the laser quantum efficiency and the frequency of the optical carrier, is then fed to the optical filter, $H(w) = |H(w)|e^{j\phi(w)}$, under test. The output field from the filter $E_o(t)$ is then transformed into an output rf current $i_o(t) = R|E_o(t)|^2$ by a photodetector of responsivity R. Provided that $w_e \ll w_o$ such that $|H(w_o)| \approx |H(w_o - w_e)| \approx |H(w_o + w_e)|$ and only the frequency component of the output current at w_e is retained, the output current is given by

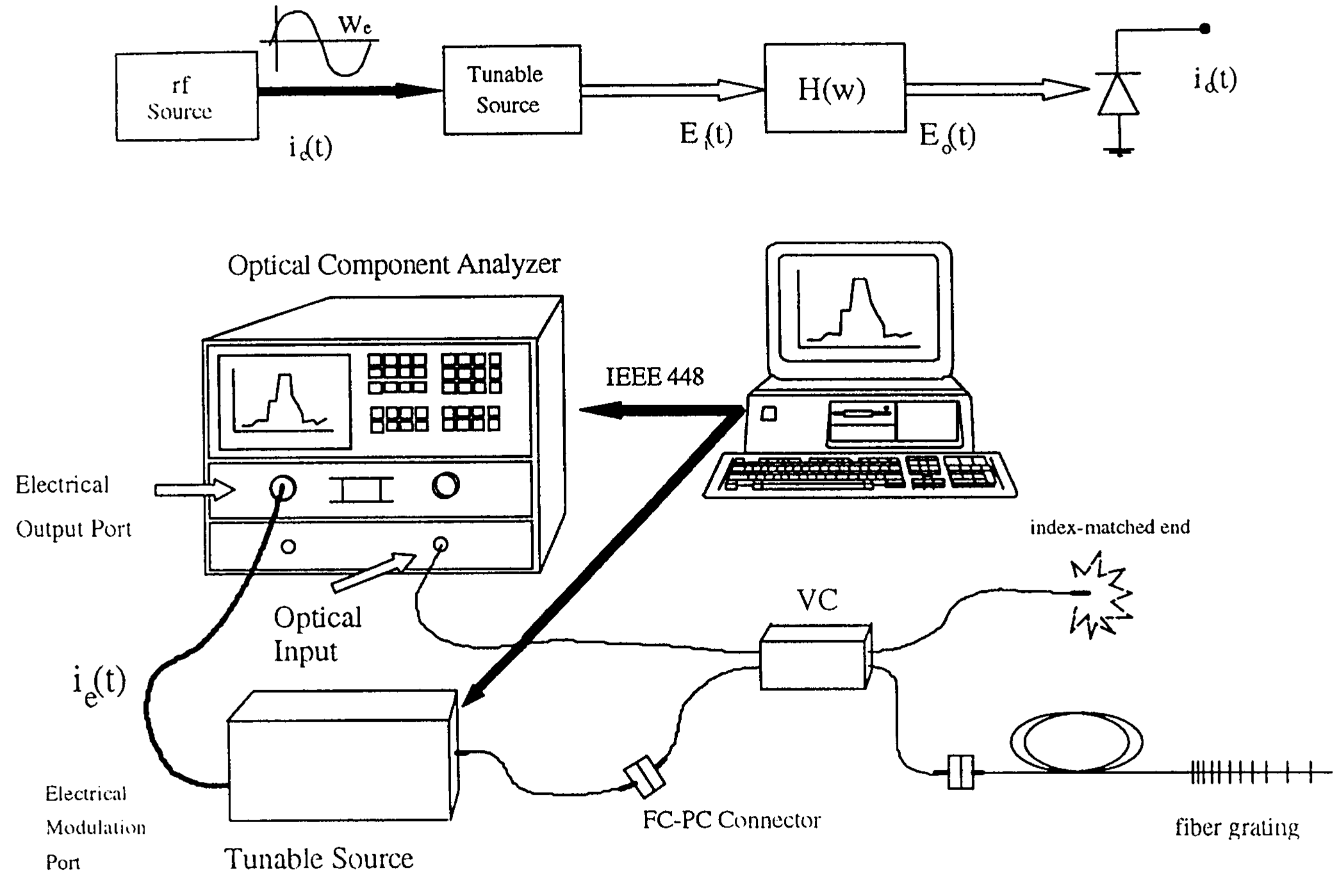


Figure 1 Basic configuration (top) of the measurement technique (bottom)

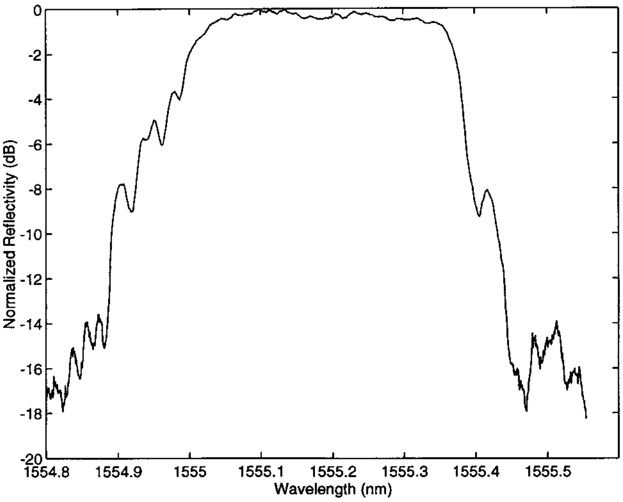
$i_o(t) = RC_L I_e m |H(w_o)|^2 \cos(w_e t - \tau(w_o) w_e) = I_o \cos(w_e t - \tau(w_o) w_e)$, where $\tau(w_o) = (d\phi/dw)_{w_o}$ represents the filter group delay at w_o. The comparison of the input and output currents yields the filter modulus and group delay for a particular optical carrier frequency. Scanning the tunable source frequency over the required wavelength range yields the spectral characterization of the optical filter.

III. MEASUREMENT SETUP

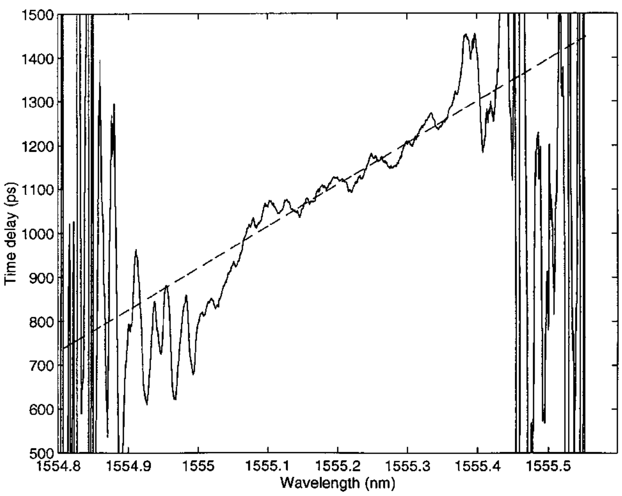
The principle described above has been applied to build the fully automatic fiber grating characterization setup shown in the lower part of Figure 1. The input sinusoidal current at $f_e = w_e/2\pi = 130$ MHz is provided by an optical component analyzer OCA (HP-8703A) configured in E/O (electrical output–optical input) operation. In this configuration, the component analyzer compares its output electrical current with the filtered w_e component of its input photocurrent, yielding a vectorial signal $|I_o/mI_e| e^{j(\arg(i_o(t)) - \arg(i_e(t)))}$, where the modulus and phase can be directly and simultaneously represented in two different screens. The rf current provided by the OCA directly modulates a tunable laser source (TUNICS-1550) capable of providing continuous wavelength scanning from 1500 to 1560 nm in steps of 100 MHz and an output power of 0 dBm. This latter figure sets the wavelength resolution of the spectral characterization. The output signal from the laser is first, before previous to any measurement, fed to the OCA optical input port, to produce an adequate calibration of the signal phase shift in the auxiliary fiber pigtails employed in the experimental setup. Once phase calibration is achieved and stored, the output signal from the laser is fed to the fiber grating through a variable coupler (VC), and the reflected signal is directed toward the optical input port of the OCA, also using the VC, as shown in the figure. Index-matching liquid is used in all connectors and also in the spare port of the VC. In the setup, the automatic synchronization of the scanning periods of both the tunable source and the OCA and the display of the results in a commercial (MATLAB) software are controlled via an IEEE 448 bus. Thus this technique is suitable for implementation in production-line environments.

IV. EXPERIMENTAL RESULTS

The above setup has been used to characterize a linearly chirped 10.5-cm-long fiber grating with a Blackman apodization fabricated at ORC labs in Southampton with the use of the moving phase mask scanning beam technique [7]. The measurement results are shown in Figure 2. Figure 2(a) shows the normalized grating reflectivity in optical decibels as a function of the wavelength. Note the flat bandpass corresponding to a linearly chirped fiber grating with a FWHM of 0.38 nm and the assymetric nature of its spectral characteristic. The group delay is shown in Figure 2(b), where, as expected, a linear characteristic is obtained in the flat-bandpass region, corresponding to a time-delay slope of 950 ps/nm. The wavelength resolution is limited to the minimum step in the wavelength scanning of the tunable source, which is 100 MHz. The delay resolution is affected by two factors: the wavelength instability of the laser source and the systematic error in the phase determination of the OCA. The RMS frequency noise of the tunable source is less than 1 GHz



(a)



(b)

Figure 2 Experimental results for a 10.5-cm linearly chirped fiber grating with Blackman apodization. (a) Modulus versus wavelength. (b) Group delay versus wavelength

($\Delta\lambda = 0.008$ nm) over a time span of 1 h. This is not a serious noise limitation, because measurements usually take 120–200 s, and wavelength changes have not been observed over such small spans. But the repeatability of the results can be affected if measurements are performed over a period of 1 h. In this case, the delay resolution is given by $\Delta\tau = \Delta\lambda(d\tau/d\lambda) = 7.5$ ps. The systematic error in the phase determination of the OCA $\Delta\phi$ leads to a delay uncertainty of $\Delta\tau = \Delta\phi/w_e$. In our case $\Delta\phi = 7$ mrad and $f_e = 130$ MHz, leading to $\Delta\tau = 8.6$ ps, although this resolution value can be reduced by increasing f_e. It must be pointed out, however, that the delay curve is averaged by the OCA; therefore the above values are reduced in practice.

V. SUMMARY AND CONCLUSIONS

We have proposed and demonstrated a new technique for the combined characterization (amplitude and group delay) of fiber gratings. The technique has the following advantages:

1. It is not based in optical interferometry.
2. It can be readily automatized, as has been presented in this Letter, where the system is computer controlled via an IEEE 448 bus.
3. It is adequate for grating characterization in a production line.

Wavelength and delay resolution are similar to those achieved by other interferometric techniques.

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