

Far-infrared nondestructive testing of sheet material

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Measurement of sheet properties with far-infrared wavelengths produces less scatter and greater resolution than similar measurements using near-infrared waves.

Superior quality control requires regular measurement of critical product characteristics. In a production environment, the best measurement techniques are those that provide a high yield of useful information within a short period of time.

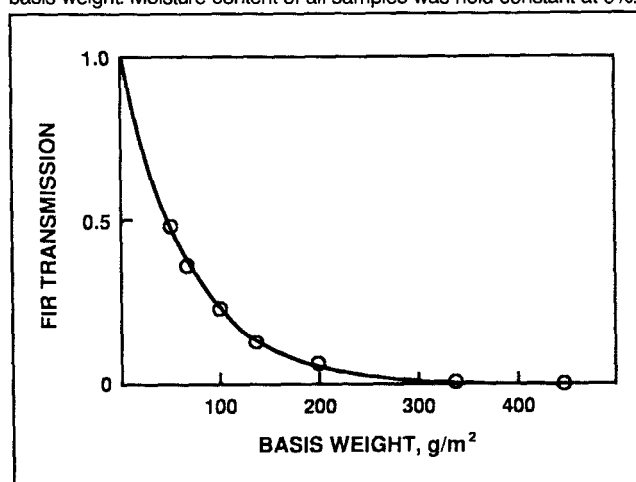
Nondestructive testing techniques are inherently efficient because they facilitate correlation of several product characteristics. For instance, the relationship between fiber orientation and curl can be established much more quickly by measuring both properties using the same set of samples. Destructive evaluation methods complicate the correlation process. If fiber orientation is evaluated using a destructive method such as zero-span tensile strength, the relationship to curl cannot be reliably established without extensive use of statistics. Obviously, this requires a lot more measurements.

Our objectives are to develop efficient nondestructive techniques based on the use of far-infrared (FIR) waves, which are ideally suited for determining the properties of dielectric sheet materials. The value of FIR in measuring basis weight and fiber orientation in paper products has already been demonstrated (1, 2). In this article, we briefly review the fundamentals of this approach and describe recent improvements that have increased the speed, reliability, and application range for this technique. To our knowledge, there is no other nondestructive test that can simultaneously measure fiber orientation and alignment within a reasonable period of time with a spatial resolution under 1 cm.

Fundamentals

The FIR portion of the electromagnetic spectrum lies between infrared and microwaves. Sometimes referred to as the submillimeter (SMM) portion, this segment of the electromagnetic spectrum has been underexploited. FIR waves are well suited for testing paper or other fibrous materials. Unlike near-infrared waves, FIR wavelengths are larger than fiber diameter, so scattering remains very

1. FIR transmission (119 μm) through paper samples as a function of basis weight. Moisture content of all samples was held constant at 6%.



low. In addition, FIR waves are less penetrating than microwaves. This enables high-spatial-resolution detection of interesting features in low-basis-weight products.

The most useful FIR source, and the one used in the experiments described here, is the optically pumped FIR gas laser. It produces a typical low-power (<100 mW) laser beam whose monochromatic wavelength can be adjusted between 50 μm and 1.5 mm by proper selection of cavity length, pressure, lasing substance, and pumping line.

At fixed wavelength, the intensity of the unpolarized beam transmitted by paper samples at constant moisture content shows a typical exponential variation with basis weight, in accordance with Beer's law. This is illustrated in Fig. 1, where transmission measurements at 119 μm are plotted as a function of basis weight for paper samples at 6% moisture content.

Consequently, a basis-weight profile can be determined using a simple transmission experiment. Moreover, because transmission coefficients vary with wavelength, a profile of moisture content can be developed using a more sophisticated procedure. Basis-weight and moisture data obtained with this approach corroborated results obtained with a high-spatial-resolution beta gauge (1).

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Even more information can be obtained if the FIR laser beam is polarized. Figure 2 shows a paper sample being rotated around the beam-propagation axis. Maximum transmission is generally observed when the sample's cross direction (CD) is parallel with the beam's plane of polarization. Minimum transmission occurs when the sample's machine direction (MD) is parallel with the polarization plane.

Continuous rotation of the sample yields transmission curves such as those presented in Fig. 3. In Fig. 3A, a single sample is rotated for two complete turns (720°), revealing the sine behavior predicted by Malus's law. The amplitude of the modulation was 22% of the mean transmission, which was less than 0.25 (25%). Figure 3B shows the results obtained by mounting two similar paper samples so that their MDs were parallel to one another. The doubled basis weight of the sample reduced the mean transmission to around 0.06 ($0.06 \approx 0.25 \times 0.25$). The enhanced modulation of the resulting transmission curve—44% of the mean transmission—is apparent. Figure 3C shows the results obtained with the same two samples mounted with their MD perpendicular to each other. As expected, mean transmission did not vary, but the polarizing effect was cancelled.

Most paper samples act as partial dichroic polarizers. Using measurements such as those in Fig. 3, it is easy to compute the maximum and minimum transmission coefficients of a sample. The ratio of these two coefficients can then be used to define an FIR or SMM anisotropy level indicator. This ratio was experimentally determined for paper samples of various weights and origins, and the results were correlated to anisotropy measurements using the zero-span tensile strength test (2, 3). The correlation being very good, the FIR anisotropy ratio is believed to be a dependable measurement of paper fiber orientation anisotropy. We have to assume that this conclusion holds for high-spatial-resolution measurements, since the destructive and statistical nature of the zero-span test is an obstacle to its uses at millimeter scale.

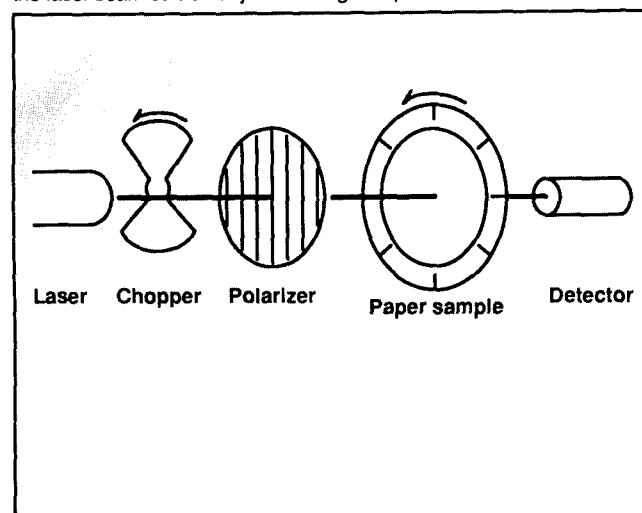
Furthermore, if the sample anisotropy is not parallel to its MD, it will be detected as a measurable phase shift in a transmission curve. (Typical nonshifted curves are illustrated in Figs. 3A and 3B.) Such an occurrence, called fiber orientation misalignment, is important in certain aspects of dimensional stability (4). Deliberate misalignments were experimentally produced and measured with good accuracy (5).

All this previous work established the FIR method as a promising nondestructive testing technique (3), but the time-consuming experimental procedure provided only rudimentary results. Efforts were made to radically improve this procedure so that it could provide reasonably fast two-dimensional mapping of basis weight, fiber-orientation anisotropy, and fiber alignment for a given paper sample.

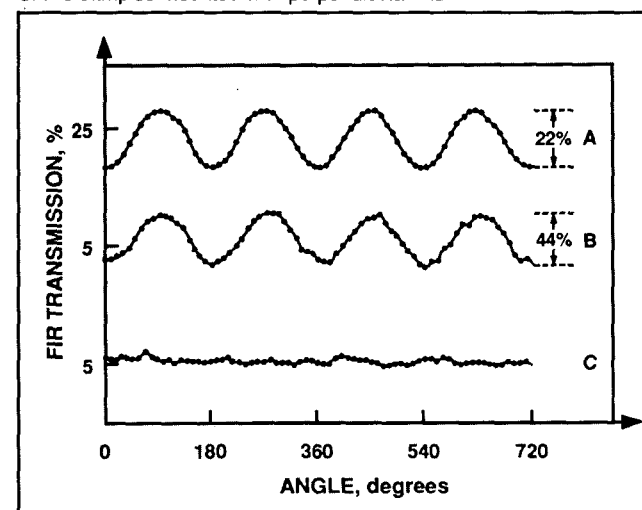
New developments

The first step in improving the technique was to eliminate the cumbersome sample rotation around the beam axis. This would allow the use of large samples, which in turn opened up the possibility of mapping the desired property simply by translating the sample. Since the significant

2. Equipment setup used in previous work. Anisotropy is measured by rotating the sample in the path of a polarized laser beam. The size of the laser beam can be adjusted using an optional lens.



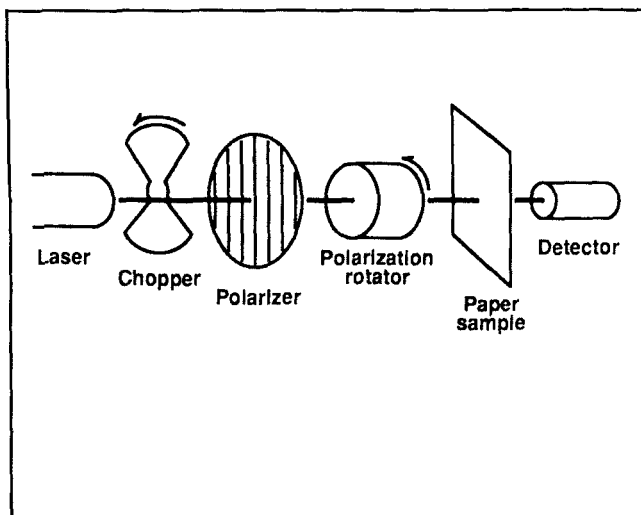
3. FIR transmission through sample as a function of the sample's angular position. A: single sample. B: two samples mounted with parallel MD. C: two samples mounted with perpendicular MD.



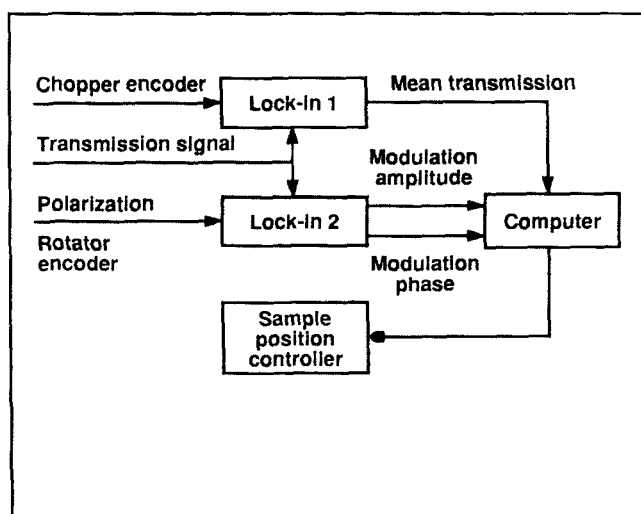
parameter is the angle between the paper MD and the beam plane of polarization, the obvious solution was to rotate the plane of polarization instead of the sample. This can be done using any of several devices. After extensive testing, we chose a beam polarization rotator made of three mirrors (6), mainly because of its availability and reasonable performance. Figure 4 illustrates the modified experimental setup. The mechanical chopper is required because the pyroelectric detectors are sensitive only to variation in beam intensity.

The basis weight, fiber orientation anisotropy, and alignment are computed from FIR transmission mean value T_m , modulation amplitude δT , and phase ϕ . In our previous experiments (Fig. 3), this information was extracted from 72 transmission measurements performed while varying the angular position in 10° steps. Our next goal was to obtain the three relevant parameters in a single measurement and speed up data acquisition.

4. Improved equipment setup. The polarization rotator eliminates the need to rotate the paper sample.



5. Signal path for synchronous detection with lock-in amplifiers



This was accomplished through synchronous signal detection with lock-in amplifiers. The lock-in amplifier is a sophisticated ac voltmeter that responds to only one frequency component of its input signal. It incorporates active filters centered on the frequency of a clean reference signal. In addition to the component amplitude, it can measure its phase relative to the reference signal (7).

A constant-speed motor drive acting on the mirror device (the polarization rotator in Fig. 4) rotates the beam plane of polarization with an angular velocity $\omega_2/2$. Thus, according to Fig. 3, transmission T through the paper sample can be represented by Eq. 1:

$$T = T_m + [\delta T \sin(\omega_2 t + \phi)] \quad (1)$$

where

t = time

With the mechanical chopper operating at frequency ω_1 , the beam intensity after the linear polarizer, I_1 , can be expressed as shown in Eq. 2:

$$I_1 = I_0(A_0 + A_1 \sin \omega_1 t + A_3 \sin 3\omega_1 t + \dots) \quad (2)$$

where

I_0 = beam intensity at the laser outlet

A = coefficients in the Fourier series expansion

Consequently, the intensity impinging on the detector, I_d , is given by the product of both expressions, as seen in Eq. 3:

$$I_d = k_0 T_m + k_1 T_m \sin \omega_1 t + k_2 \delta T \sin(\omega_2 t + \phi) + \dots \quad (3)$$

where k_n represents constants. Higher as well as difference frequency terms are omitted.

Two lock-in amplifiers operating at ω_1 and ω_2 are used to sort the values of $k_1 T_m$, $k_2 \delta T$, and ϕ . By comparing with a first measurement on a reference sample of known T_m , δT , and ϕ , the characterization of any other sample is straightforward. Careful choice of ω_1 and ω_2 minimizes the interference of difference components with the two required signals. The electronics setup is illustrated in Fig. 5. Reference signals originate from shaft position encoders on the chopper and the polarization rotator.

This system was used to perform two-dimensional mapping of basis weight, fiber orientation anisotropy, and fiber alignment on various samples. Results are presented in the next section.

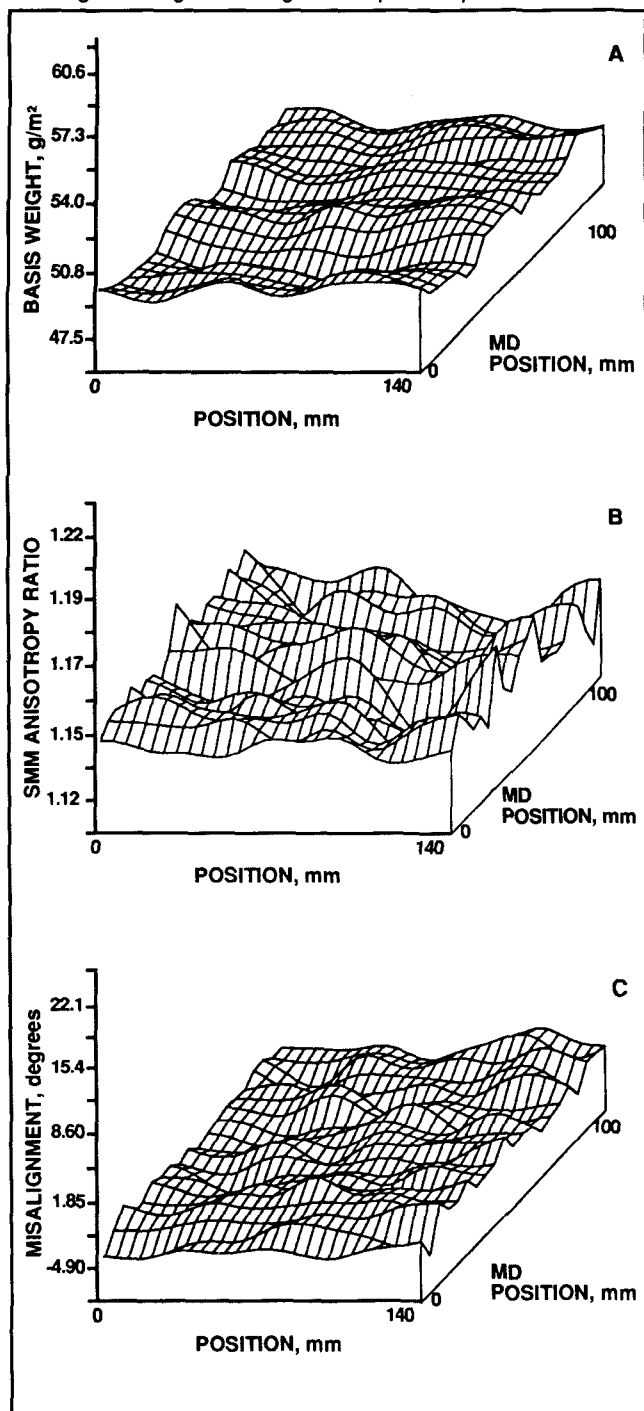
Results

All results reported here were obtained under the same experimental conditions. The laser was operated at 70- μ m wavelength. The beam diameter on the sample was 1 cm. The sample transmission was surveyed on a 10-cm $\times$ 14-cm area with a 5-mm $\times$ 5-mm grid, which amounts to 609 individual measurements. The normalization values for the mean transmission, the modulation amplitude, and phase were determined with a previously characterized grid polarizer. These values were checked between each scan line, i.e., every 29 points, to monitor the system stability. Chopper frequency ω_1 was 108 Hz; polarization rotator frequency ω_2 was 21 Hz. This setup consistently yielded reproducible results with various types of paper (newsprint, photocopy grade, cardboard, tissue) and fabrics (woven and nonwoven nylon and polyester).

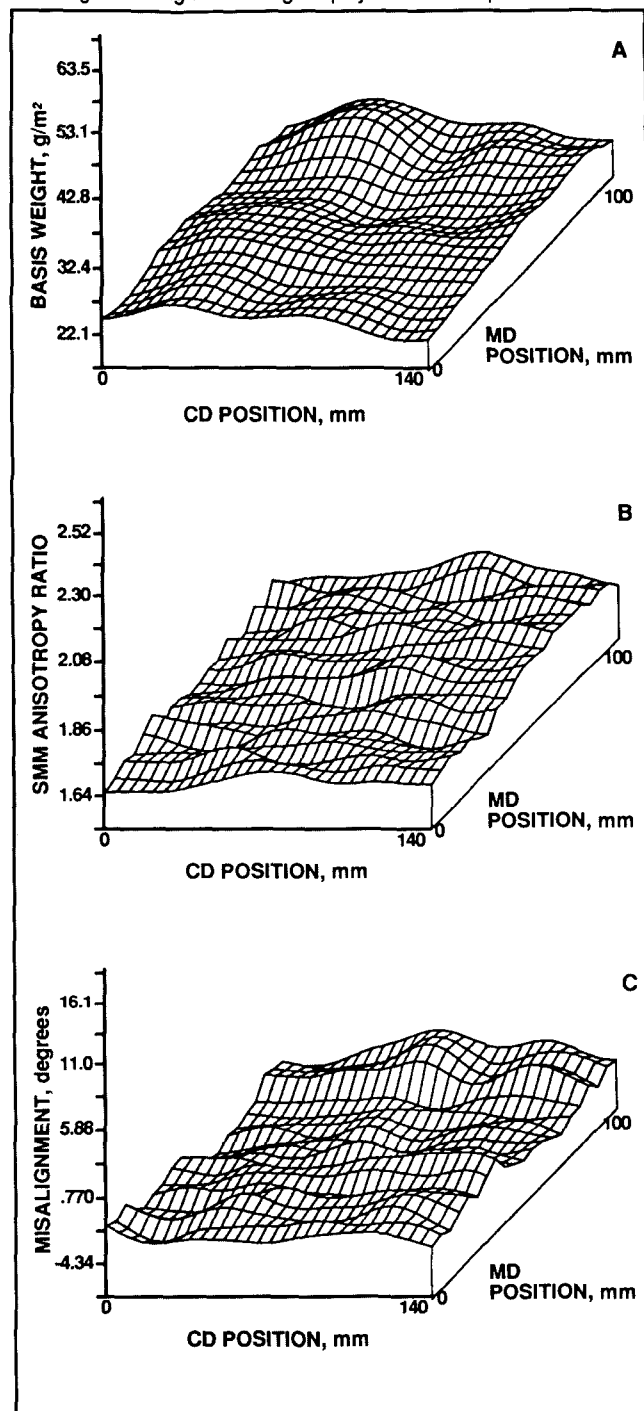
To illustrate the range of materials that can be tested with FIR waves, we present typical results for two different sheets. Figure 6 illustrates the results for newsprint made of short, natural wood fibers. Figure 7 shows the results for a nonwoven fabric made of long, synthetic polyester fibers. Each figure provides an axonometric view of basis weight, anisotropy ratio, and alignment angle for each material.

Since FIR transmission was repeatedly demonstrated to follow Beer's law, the basis-weight scale is established by measuring absolute transmission. The mean FIR transmission value and the mean basis weight of the sample, measured on a precision weighting balance, provide the necessary transmission coefficient. The SMM

6. Axonometric view of (A) basis weight, (B) anisotropy ratio, and (C) fiber-alignment angle for a 45-g/m² newsprint sample



7. Axonometric view of (A) basis weight, (B) anisotropy ratio, and (C) fiber-alignment angle for a 25-g/m² polyester felt sample



anisotropy ratio value is 1.00 for an isotropic sample, such as a typical square handsheet. According to our previous work (2), an SMM anisotropy ratio equal to 1.20 would correspond to a 60° result with the zero-span tensile strength test. Finally, the misalignment axis scale gives the angle between the sample's MD and the actual direction towards which its fibers tend to orient.

Discussion

It is beyond the scope of this article to discuss the physical

aspects of these results. Many experimental conditions can easily be changed. Beam size can be adjusted from a few square millimeters up to several square centimeters. With this range of spatial resolution, it is possible to study paper formation or conduct a large-scale survey. Depending on the material and the FIR wavelength, the sample basis weight can be much higher or significantly lower.

The two main drawbacks are the bulk and complexity of the laser itself and the duration of the tests. Despite the two-order-of-magnitude gain in speed, there is still room for improvement. The polarization rotator we used

is a prototype. Its design could be modified to allow higher revolution rates and, consequently, faster settling times for the lock-in amplifier. This would reduce the 10-s delay between each measurement. Sample displacement also contributes to the delay between measurements, and a faster bidimensional translation table is now being installed. As for the laser, the one we used was designed for research activity in various fields. The National Optics Institute is developing a smaller, simpler, and more stable laser better suited to this type of application.

Nevertheless, this testing method was used to track the possible causes of small-scale dimensional stability problems such as cockling and bagging in production newsprint. CD strips from various machines were characterized at high spatial resolution with our FIR technique, and extensive data analysis revealed significant information that could be related to the faulty machines (8).

Conclusion

In previous work, we reported on the use of far-infrared (FIR) waves to measure basis weight, fiber orientation anisotropy, and fiber alignment in dielectric sheet materials. This article describes hardware modifications that have led to significant improvements in the speed and accuracy of the FIR technique. The ability to perform nondestructive, high-resolution studies could lead to better understanding of sheet structure and better control of manufacturing processes.□

Literature cited

1. Drouin, B., Gagnon, R., Bergeron, M., and Boulay, R., Preprints of the 74th Annual Meeting of the Technical Section of the CPPA, Montreal, Jan. 1988, p. A 123.
2. Boulay, R., Drouin, B., and Gagnon, R., *J. Pulp Paper Sci.* 12(1): J26(1986).
3. Boulay, R., Drouin, B., and Gagnon, R., U.S. pat. 4,654,529 (Oct. 6, 1986).
4. Koskimies, J., Preprints of the 72nd Annual Meeting of the Technical Section of the CPPA, Montreal, Jan. 1986, p. A123.
5. Gagnon, R., Drouin, B., and Bergeron, M., *Journal des Pates et Papiers* 3(4): 29(1987).
6. Johnston, L. H., *Appl. Opt.* 16(4): 1082(1977).
7. Meade, M. L., *Lock-in Amplifiers: Principles and Applications*, Peter Peregrinus Ltd., London, U.K., 1983.
8. Gagnon, R., Drouin, B., Dicaire, L. G., and Bernard, P., Preprints: 1989 Newsprint Conference, CPPA-TS, Que., Sept. 1989, p. 115.

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