Embedded high-speed solid-state fibre optic sensor

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Abstract: This paper presents a new concept for measuring water content from the press section to the reel to facilitate better control via small, robust, fibre optic based sensors embedded in the paper machine. Off-machine solid state devices and fibre optic components can efficiently deliver the required wavelengths of infrared radiation simultaneously to multiple locations on the paper machine. Traditionally, thermal sources such as quartz-tungsten-halogen (QTH) lamps have been used with mechanical modulation for spectroscopic moisture measurements, which limits frequency response to about 200 Hz in the best cases. The technology discussed in this paper enables direct modulation of the source at MHz frequencies, effectively eliminating the frequency response limitation to scan speed, allowing an order of magnitude faster scan speeds than traditional scanners, and thus faster control.

THE USE OF THESE COMPONENTS has enabled the development of the industry's smallest scanner for CD profile measurements. The small cross-sections of the CD scanner and MD fixed-point sensors enable them to be installed in very space-constrained locations in the wet-end of the paper machine. Successful measurement has been demonstrated from the dry end of the paper machine up to and including the pick-up felt location with a combination of CD scanning and MD fixed-point sensors. Results of both MD and CD measurements obtained from various paper machines around the world are presented and discussed.

Variations in water content change fibre swelling, web tensions and mechanical properties of the final product in the manufacturing of paper. When water is maintained at uniform distributions in the cross direction, and removed at optimal rates along the length of the machine, the process can be run with lower draws, reduced tensions and shrinkage so that on-machine performance, converting and printing operations will run better. The historical challenge has been the lack of reliable measurements outside of the reel or size press locations.

This is understandable due to the more spatially-restrictive and hostile environments of dryers and press sections. The restrictive space constraints exclude large cross-section conventional scanners. The excessive heat of the dryers or the high humidity, dirt and corrosion of the press section exclude extended use of conventional sensors. Fibre optics are an ideal solution to these challenges. They can be used to deliver the infrared (IR) radiation required for moisture sensing in the restrictive and hostile environments, while keeping all the sensitive optoelectronic components off the paper machine (remote from sensing location). Also, now that these remotely located optoelectronic components are no longer required to be at the paper surface, the size of the sensor head is significantly reduced, allowing for a greatly reduced cross section of the CD scanners and MD sensors. Fibre optics do have some drawbacks which must be addressed, especially those that include scanning fibre optic cable. For example, the design must preserve the minimum bend radius [1] of the fibre, and deal with bend loss and its functional dependence on both wavelength [2] and temperature [3].

SENSOR SYSTEM FEATURES

In this new sensor design, high-brightness superluminescent light emitting diodes (SLEDs) are used instead of the quartz-tungsten-halogen (QTH) lamps found in more traditional moisture sensors. SLEDs have peak spectral power densities of approximately -5 dBm/nm in a single-mode optical fibre. The spectral power density from a more conventional thermal source (i.e. QTH lamp) launched into a single mode fibre would be around -70 dBm/nm. That is, for a given spectral bandwidth, there would be approximately 2,000,000 times less power with a QTH source than from the SLED in a single mode fibre. In short, QTH sources are not designed for use with fibre optic components requiring the use of expensive and more cumbersome large core optical fibres. Even then it is a very inefficient way of utilizing the optical energy from a thermal source.

Figure 1 demonstrates clearly what this means to the papermaker. In the top half of the display, a typical QTH source was used with a fibre optic delivery system to measure the process at the exit of a press section. The scan average data is reasonable, but the profile data is not usable for control or even troubleshooting. The system was then switched over to the new SLED technology. The subsequent data (lower half of display) is far clearer, making the 3 mm data box widths meaningful, providing real benefits to the paper maker.

Lock-in detection techniques are ubiquitous with the IR moisture sensing used in the paper industry. For thermal sources, such as QTH

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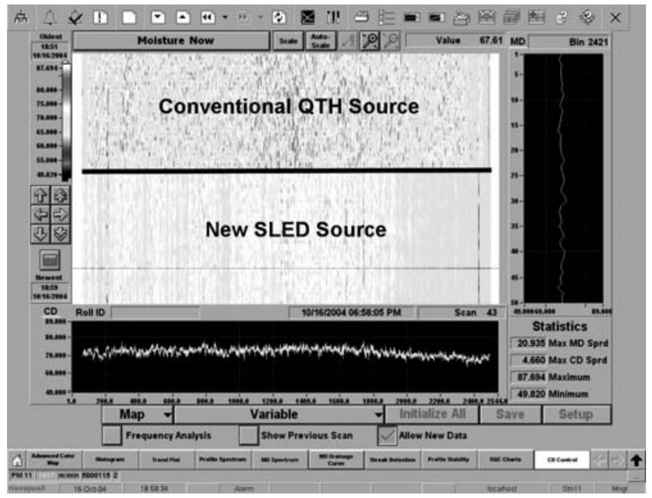

FIG. 1. Conventional QTH Source vs. SLED Source.

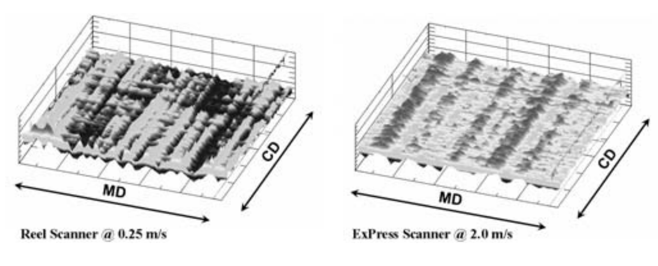

FIG. 2. Comparison of the Reel Scanner and the ExPress Scanner

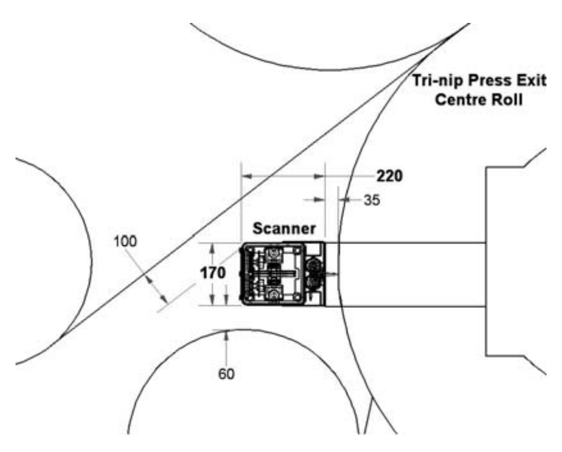

FIG. 4. Scanner Cross-section 220 x 170 mm.

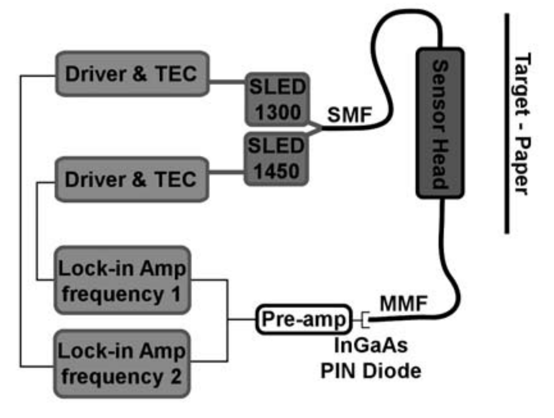

FIG. 3. Sensor Schematic.

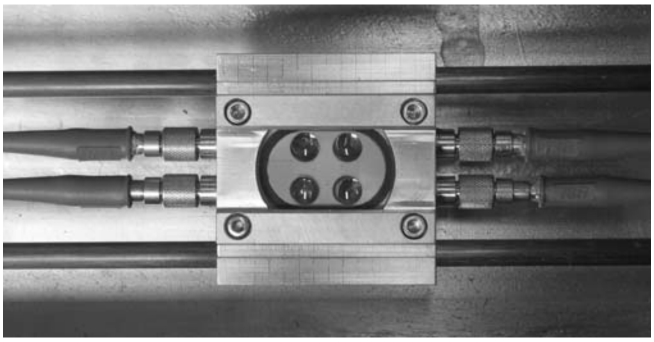

FIG. 5. Sensor Head, 210 grams, 55 x 50 x 16 mm.

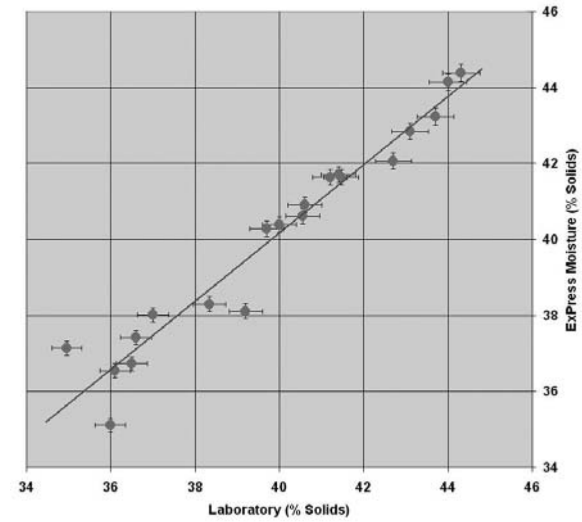

FIG. 6. Dynamic Sensor Verification.

lamps, lock-in detection is limited to source modulation frequencies of less than 10 kHz and typically less than 1 kHz because mechanical techniques are used (e.g. tuning fork, rotating filter wheel). This typically gives sensor bandwidths of 100 to 200 Hz, which of course limits the scanning speed and spatial resolution. With SLEDs, the source injection current can be directly modulated in the MHz regime, allowing sensor bandwidths of hundreds of kHz. An additional benefit is that SLEDs have lifetimes of greater than 20 years, whereas QTH lamps are rated for about 4000 hrs (½ year).

The higher modulation frequencies, combined with lower effective sensor head mass enable faster scanning. One of the benefits of faster scanning to the papermaker is demonstrated in Fig. 2. The data in the left hand topographical map was taken from the pre-existing QCS (quality control system) scanning at 0.25 m/s. The data in the right hand topographical map was taken from ExPress CD, scanning almost an order of magnitude faster. Both sets of data were taken simultaneously, with the data from the ExPress CD unit clearly showing that there is a significant MD oscillation with stable CD profile. The MD oscillation frequency and the slow speed of the reel scanner were matched in such a way to cause aliasing, creating an apparent CD oscillation that didn't exist. CD controls based upon the reel data would have to be significantly filtered or they would induce additional CD variations. Additionally, it can be seen from the ExPress data that

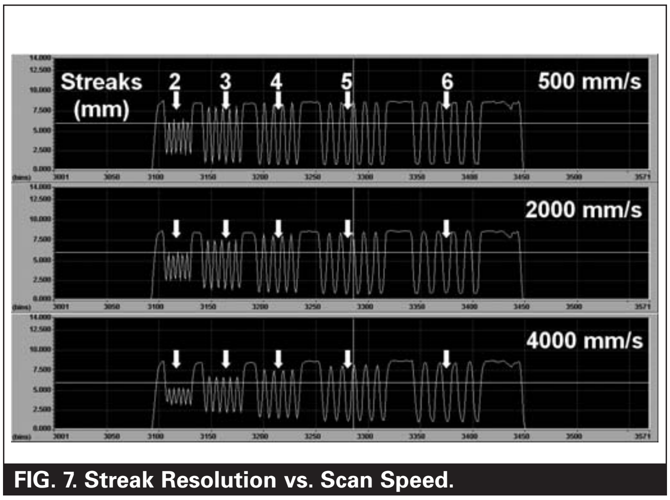

FIG. 7. Streak Resolution vs. Scan Speed.

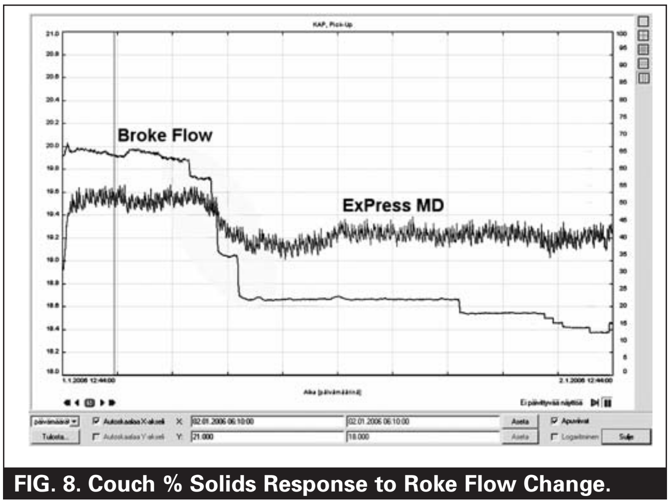

FIG. 8. Couch % Solids Response to Roke Flow Change.

there is a CD streak that needs attention, which was not obvious from the reel scanner data.

Figure 3 shows a schematic set-up of the moisture sensing system constructed using SLEDs. Two laser diode controllers were used to control both the temperature and drive current to the SLEDs. An SLED with centre wavelength and full width half maximum line-width specification of 1310±20 nm and >45 nm respectively was used as the reference source and an SLED with centre wavelength and full width half maximum line-width of 1450±10 nm and >40 nm respectively was used as the measure source. These wavelengths were chosen because high power SLED sources are readily and economically available at these wavelengths and, conveniently, there is a water absorption peak around 1450 nm.

he light from the SLEDs is then combined using a 3 dB single-mode fibre optic directional coupler. The two output arms of the directional coupler are then connected to a multimode fibre using FC/APC to FC/APC mating sleeves. The outputs of the multimode fibre were then coupled to two multimode step-index delivery fibres using SMA 905 to SMA 905 mating sleeves. These delivery fibres were then terminated at the optical head, which images the light onto the paper under test. A portion of the light that is scattered from the paper is captured by a lens and coupled into a multimode step-index receiving fibre, which was of the same type as the optical head end of the delivery fibres.

Light from the output end of the receiving fibre was then coupled onto an InGaAs p-i-n photodiode. The output from the photodiode was then fed to lock-in amplifiers via a transimpedance gain amplifier, which demodulated the reference and measurement signals. The output voltage from the lock-in amplifier has selectable low pass-filters on the output; this filter is typically set at 1 ms or 300 (s. The two voltages from the lock-ins were then fed into a computer for analysis.

SCANNER FEATURES

For press section installations, both the scanner and sensor head must be as simple as possible to reduce size and increase robustness. A cross-sectional diagram of the CD scanner used to traverse the optical head across the sheet can be seen in Fig. 4. It is unique in that the sensor head, Fig. 5, is driven back and forth across the sheet using the fibre optic cables that deliver the light to and from the sheet. The sensor head rides on two carbon fibre composite rails that are under tension. By eliminating the power-track completely and removing all electronics and associated cooling from the sensor head, the mass of the sensor head has been kept very low. This, in combination with the high strength-to-weight ratio of the carbon fibre rails, allows the head to travel very quickly in an almost perfectly straight line, immune to any negative effects of paper machine vibrations.

This design also allows for the use of essentially inert materials, further increasing the robustness of the measurement. As well as the usual motor and position sensors you would expect in a scanner, we have also included an automatic standardization and a cleaning station that ensures that the sensor window remains transparent and dry during operation.

RESULTS

With new measurements destined for previously unmeasured locations, one of the concerns is the accuracy of this new data. Of course it can be very challenging to obtain suitable samples from the machine in these locations, but some work has already been successful in showing the linearity of the calibration from dynamic laboratory checks. Figure 6 shows multiple samples taken over a reasonable range of moisture at the exit of a tri-nip press. Laboratory tests have shown that the absolute calibration accuracy of the new moisture sensor is ±0.5% moisture.

Streak resolution has been demonstrated to be far superior to traditional single-sided infrared (SSIR) measurement techniques. Figure 7 shows results from scanning at different speeds over various streak widths. The 1/e streak resolution is <3 mm at scan speeds less than 2000 mm/s and <4 mm even at 4000 mm/s scan speed.

One of the advantages of several MD sensors is the economical segmentation of the machine. It is of vital importance to be able to identify what part of the process is causing the deviation from target so that the correct parameter can be manipulated. With sensors placed as far up the process as the pickup felt, it is easy to identify whether a change is coming from the press section itself, or a wet end formulation change.

Figure 8 shows the sensitivity to stock changes. In this example, the dewatering change in the forming section was detected by an MD sensor measuring the paper at the pick-up felt location following the Couch. In this 24 hour trend, we see the moisture drop as the broke flow changed significantly.

CONCLUSION

A new concept for measuring water content from the press section to the reel via small, robust, fibre optic based sensors embedded in the paper machine has been presented. Utilizing high-brightness superluminescent light emitting diodes and fibre optic components efficiently delivers the required wavelengths of infrared radiation simultaneously to multiple locations on the paper machine. The use of these components has enabled the development of the industry's smallest scanner, at 220 x 170 mm for CD profile measurements. The small CD scanner and MD fixed-point sensor cross-sections have enabled us to present data from very space-constrained locations in the wet-end of the paper machine.

Successful measurement has been demonstrated from the dry end of the paper machine up to and including the pick-up felt location with a combination of CD scanning and MD fixed-point sensors. Traditionally, thermal sources such as quartz-tungsten-halogen (QTH) lamps have been used with mechanical modulation for spectroscopic moisture measurements, which limits frequency response to about 200 Hz in the best cases. At an order of magnitude faster frequency response the new sensor gave a repeatability of 0.06% at press section water weights. Results were shown for both MD and CD measurements obtained from various paper machines around the world.

LITERATURE

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Résumé: Cette communication présente un nouveau concept permettant de déterminer la teneur en eau, de la section des presses à l'enrouleuse, afin d'avoir un meilleur contrôle grâce aux petits capteurs robustes en fibre optique intégrés dans la machine à papier. Les éléments à fibre optique et les dispositifs à semi-conducteurs hors machine peuvent efficacement produire simultanément les longueurs d'ondes requises de rayonnement infrarouge à plusieurs endroits de la machine à papier. Traditionnellement, des sources thermiques comme des lampes halogènes au tungstène sous tube de quartz ont été utilisées avec des modulateurs mécaniques pour déterminer la teneur en eau à l'aide d'un spectroscope, ce qui limite la réponse en fréquence à environ 200 Hz dans les meilleurs cas. La technologie faisant l'objet de discussion dans la présente communication permet la modulation directe de la source à des fréquences en MHz, et ainsi d'éliminer efficacement la limite de la réponse en fréquence à la vitesse du balayage. Elle permet aussi des vitesses de balayage d'un ordre de grandeur plus rapide que les scanners traditionnels et, ainsi, un contrôle plus rapide.

L'utilisation de ces éléments a donné lieu au développement du plus petit scanner de l'industrie pour la détermination du profil ST. Les petites sections transversales des capteur à balayage du scanner ST et des capteurs de points fixes SM permettent de les installer dans des endroits très exigus à la partie humide de la machine à papier. Nous avons pu procéder à des déterminations positives, de la partie sèche de la machine à papier jusqu'au feutre leveur inclusivement, en combinant les capteurs à balayage ST et les capteurs de points fixes SM. Les résultats des deux déterminations SM et ST obtenus de diverses machines à papier dans le monde sont présentés et font l'objet de discussion.

Reference: HARAN, F., BESELT, R., MACHATTIE, R. Embedded high-speed solid-state fibre optic sensor. *Pulp & Paper Canada* 108(12):T195-198 (December 2007). Paper presented at the 93rd Annual Meeting in Montreal, QC, February 5-9, 2007. Not to be reproduced without permission of PAPTAC. Manuscript received on December 21, 2006. Revised manuscript approved for publication by the Review Panel on September 10, 2007.

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