Wavelength tunable optical time-domain reflectometry based on wavelength swept fiber laser employing two-dimensional digital micro-mirror array

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A R T I C L E   I N F O

Article history:
Received 14 October 2008
Received in revised form 27 November 2008
Accepted 28 November 2008

A B S T R A C T

We demonstrate a cost effective wavelength tunable optical time-domain reflectometry (OTDR) for wavelength division multiplexing passive optical networks (WDM-PON). In order to realize the unique wavelength tunable optical time-domain reflectometry (OTDR), the wavelength swept fiber laser was developed by a digital micro-mirror array device (DMD), and the correlation OTDR (COTDR) technique was used. We successfully detected the fault location at the remote node fibers with 20 m resolution and fast wavelength setting speed of ~15 μs in conventional band (C-band).

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1. Introduction

Wavelength division multiplexing passive optical network WDM-PON is considered as one of the potential solutions for next generation access network [1,2]. In order to realize the WDM-PON in access networks, cost-effective optical components and managing techniques are vitally required. Fault detection in local transmission line is of high concern to guarantee reliable operation of the WDM-PON. Fiber faults have been detected by using an OTDR in conventional communication systems. However, in the case of WDM-PONs, a large number of wavelength sources are used carrying the signals to the many drop fibers after the remote node. The conventional OTDR using the single fixed wavelength light signal would have difficulties to detect fault locations due to the inherent wavelength selectivity of the embedded remote node components in WDM-PON systems. To solve these problems, a tunable OTDR has been proposed based on tunable diode lasers [3–5] which is, however, regarded as rather an expensive solution to be deployed in access networks. In a recent, a tunable laser using an SOA and an Opto-VLSI processor has been demonstrated with flexible lasing wavelength tunability [6]. However, the reported tunable laser has too small tuning range and cannot generate high power signals due to the phase hologram driven by liquid crystal. In this paper, by developing a unique wavelength swept fiber laser system based on DMD, we propose a new wavelength tunable fiber-fault location detecting technique for service monitoring of the WDM-PON systems. A wavelength swept fiber laser system was used as an optical source for a wavelength tunable OTDR (WTOTDR) and the fault locations in the drop fibers were successfully detected. Operation principle and characteristics of the proposed WTOTDR are discussed.

2. Characteristics of wavelength swept fiber laser

By utilizing the spectral dispersion of a diffraction grating and the pixelated spatial light selective property of DMD, we can combine DMD with a diffraction grating to be used as a tunable filter in a fiber laser cavity. A schematic illustration of the DMD based wavelength swept fiber laser is shown in Fig. 1. A ring laser cavity was formed using erbium doped fiber (EDF) as a gain medium and its saturated output power is 13 dBm with small signal gain of more than 30 dB over the signal wavelength range from 1525 to 1562 nm. The fiber polarization controller and the output coupler optimized the laser output power. The optical isolator provided unidirectional optical path in the laser cavity and the quarter-wave plate was used to minimize polarization effects. The DMD (DLPTM in Texas Instrument, the DMD part number: -1076-46C) was used as a spectral filtering element for tuning the laser wavelength. The DMD consists of individually addressable aluminum micro-mirrors whose mirror size is 13.68 μm. The array size is 1024 × 768 in square grid pixel arrangement and the glass window of DMD is optimized for near infrared wavelength from 900 to 2000 nm. Depending on the control signal applied memory cell, each mirror can be rotated by ±12° from the unpowered position. The mirror switching time is less than ~15 μs. Due to the high coupling loss between collimator and the DMD, the total loss of laser cavity was 4.5 dB. In Fig. 1, the input beam, from the one arm of the fiber-optic circulator, is collimated onto a diffraction grating that disperses the wavelength components at different angles. The output beam diameter of collimated light was 2.07 mm at 1/e² of peak intensity and the full-angle beam divergence was 0.055°. The distance between collimator and diffractive grating was about 50 mm. The diffracted rays from the grating were re-collimated by the following biconvex lens with a focal length f = 51 mm, and then horizontally projected on the DMD. The spectral components of the diffracted beam will form
stripes of ~19 mm length at the surface of the DMD. The mirror arrays in DMD were electronically inclined with ±12° against the vertical direction. When mirrors are tilted with −12°, the incident light on the mirrors is deflected to the outside of cavity, and in the tilted state of mirrors with +12°, the light is reflected back into the laser cavity for lasing. Therefore, this mosaic of discrete switching micro-mirrors and subsequent reflection feedback into the laser cavity can serve as a wavelength selecting spatial light modulator. From this pixelated spatial light modulation, the lasing wavelength control could be achieved by selecting corresponding spectral positions on DMD. In order to select the lasing wavelength, the positively tilted area was vertically formed in a thin rectangular shaped pattern with an 18 × 768 section of mirror mosaic. The number of mirrors determines the intensity and spectral resolution of the reflected light. In this experiment, we use the diffraction order \( m = 1 \) of a grating (600 grooves/mm, blaze angle = 28.41°, ruled; Optometrics LLC) with grating period \( (d) \) is 1.6 \( \mu \)m, at a nominal wavelength of \( \lambda = 1550 \) nm. The diffraction angle \( (\theta_d) \) was measured as ~21° with an incident angle \( (\theta_{in}) \) of 35°. The reciprocal of the special dispersion \( (\alpha) \) of the grating-lens combination, which describes the relative position \( (x) \) of the frequency components across the horizontal direction of DMD surface, is given by [7]

\[
\alpha = \frac{\partial \lambda}{\partial x} = \frac{d \cdot \cos \theta_d}{f \cdot m}
\]  

(1)

from which \( \alpha \) was calculated as 29.29 nm/mm. The size of micro-mirror is 13.68 \( \mu \)m. Since the diffraction spectrum horizontally extends on the DMD surface, the pitch corresponds to ~13 \( \mu \)m separation between consecutive micro-mirror lines is 0.037 nm/micro-mirror line. The spectral resolution of the filter is determined by the minimum size of the focused beam diameter \( (d_{out}) \) on the DMD surface and is defined as below,

\[
d_{out} = 4 \cdot \frac{\cos \theta_{in}}{\cos \theta_d} \cdot \frac{f \cdot \lambda}{\pi \cdot d_{in}}
\]  

(2)

where \( d_{in} \) is the diameter of input beam and was measured as 2.07 mm at 1/e² of peak intensity. The minimum size of beam was calculated as 0.221 mm and this corresponds to 17 lines of micro-mirrors. From the Eq. (1), the spectral width in DMD based optical filter can be calculated as

\[
\Delta \lambda = \alpha \cdot D \cdot N
\]  

(3)

where \( N \) is the number of ON state mirror lines within a period contributing to the output and \( D \) is the separation between consecutive micro-mirror lines. It was found that 18 columns of mirrors were optimal value for the fiber laser tunability, which corresponds to about 0.67 nm in the spectral dispersion plane of the DMD. The

Fig. 1. The schematic of wavelength swept fiber laser system.

Fig. 2. (a) The wavelength spectra of the lasing signal depending on the DMD positions. (b) Corresponding lasing wavelength change and optical power variation according to the DMD pixel positions.
The experimental results for wavelength tuning in the fiber laser are summarized in Fig. 2. There is typically about 25 dB extinction ratio between positive and negative tilt states with a fast setting speed of \( \frac{1}{24} \text{s} \). When the center position of reflecting mirror columns moved from 175 to 791 pixel-address (one pixel equals to one mirror) in 22 pixel interval, the laser output spectra of the proposed laser were measured and are shown in Fig. 2a and b, respectively. As the center position of reflecting mirror columns is changed, the lasing wavelength is linearly varied from 1538.15 to 1560.59 nm. Note that the center wavelength can be arbitrarily selected over the dense wavelength division multiplexing (DWDM) international telecommunication union (ITU) channel grid in the proposed scheme. The fiber laser output showed the signal-to-noise ratio better than 40 dB within the whole tuning range of 23 nm, and the linewidth of about 0.11 nm measured with 0.01 nm resolution optical spectrum analyzer. The tuning resolution of lasing wavelength in terms of the reflecting mirror array position was about 0.037 nm/pixel and the measured minimum wavelength selectivity was about 0.1 nm with 3 pixel-address change of the center position of reflecting mirror columns. The output power of laser varied with its lasing wavelength due to the overall gain spectrum, yet the maximum power difference between lasing peaks was about 0.5 dB.

3. Design and characteristics of wavelength swept optical time-domain reflectometry

In a standard OTDR, high energy pulses of \( \sim 5 \) ns or \( \sim 1 \) \( \mu \)s duration are sent down the fiber. Measuring the time delay between the
emitted pulse and detected back reflection for a given refractive index of the fiber allows calculation of the distance of the reflective discontinuities down the fiber. Absorptive discontinuities can be monitored as well, provided that they affect the detectable Rayleigh backscatter signal. The proposed WTOTDR is based on the principle of correlation OTDR (COTDR) [8]. A continuous stream of laser pulses at a cycle frequency of kHz to several MHz is sent down the fiber. The pulse stream comprises of digital pseudo-random numbers, number ‘0’ corresponds to a low level of laser power and number ‘1’ corresponds to a high level of laser power. The back-reflected stream of pulses is digitized and correlated with the transmitted digital pseudo-random number stream. A high quantity of correlation at specific delays allows calculation of the distance of the reflective discontinuities, if we know the speed of light in the fiber. The primary advantage of COTDR over the standard OTDR lies in a better signal-to-noise factor in integration of reflected signal over a fixed amount of time. The propose WTOTDR was shown in Fig. 3. In Fig. 3, a digital pseudo-random numbers generator sends a continuous stream of states ‘0’ and ‘1’ at a selectable clock rate from kHz to MHz. The state of a wavelength swept fiber laser output was modulated by acousto-optic modulator (AOM), and the modulated signal is transmitted to the fiber network via a fiber-optic circulator. Backward reflections from the fiber discontinuities enter the same circulator. A digital correlator is responsible for delaying the emitted data stream and correlating it with the digitized reflected signal stream. The result is fed into 256 up/down counters of 16 bit length. Each counter integrates the correlation of the stream at one cycle additional time delay. If several events are detected, the numbers in the counters directly relate to the strengths of the reflective events.

In order to evaluate the performance of the proposed WTOTDR, we measured the back reflection traces for the test fiber link which have intentionally located three faults at 0.8, 0.96 and 2.83 km span, respectively. The length of the test fiber link was 5.96 km. The fault detection result of proposed WTOTDR was shown in Fig. 4. As shown in Fig. 4, clear indications of faults at different locations were observed. The calculated fault positions exactly matched to the original fault positions in the test fiber link and the dynamic range measured on the WTOTDR trace was more than 20 dB for 1 μs probe pulse. The experimental setup to evaluate the performance of the proposed WTOTDR is shown in Fig. 5. It consists of WTOTDR, followed by a 32 channel 100-GHz channel spacing arrayed waveguide...
grating (AWG) and four different branch fibers of varying length with 50.9, 33.33, 71.96 and 77.2 km are connected to the output ports of the AWG. At the end of each branch, commercial polished connector (PC) was used as a reference marker. Each test fiber branch has intentionally located fiber faults. The first test fiber branch has one splicing point for fault at 24.99 km. The second and third test fiber branches have also intentionally located one PC-connector connection point at 4.75 and 20.70 km, respectively. The third test fiber branch has both one splicing point at 20.70 km and one connector connection point at 25.69 km. The wavelength of WTOTDR was tuned to the center wavelength of each channel by varying the pixel position of the DMD. The –8 dBm power of laser signal was injected into the transmission fiber through the OTDR system at 1550.12, 1549.31, 1548.51, and 1547.71 nm, respectively. The measured backward reflection traces of WTOTDR at each wavelength of wavelength swept fiber laser were shown in Fig. 6. The spectral width of lasing signals was about 0.11 nm.

The problem with the previous tunable OTDR approach was the poor signal-to-noise ratio arising from the coherent Rayleigh noise (CRN) on the backscattered signal [3,9]. This occurs due to the interference of a large number of discrete backscattering events at different positions in the fiber causing speckle phenomenon. The phase noise resulting from the above phenomenon is converted to intensity noise at the receiver and manifested as temporal amplitude fluctuations on the backscattered Rayleigh signal. This phase correlation can be reduced by increasing the source bandwidth [10]. The standard deviation of the coherent Rayleigh noise as a fraction of the Rayleigh scattering signal is given by

\[ f_{C,R,N} = \sqrt{\frac{V_g}{4\Delta z \Delta v}} \]  

(4)

where \( f_{C,R,N} \), \( V_g \), \( \Delta z \), and \( \Delta v \) are the standard deviation of the coherent Rayleigh noise, group velocity of light in the fiber, spatial resolution, and source bandwidth of the OTDR, respectively. For a tunable OTDR employing narrow linewidth laser source (\(~0.5\) GHz) and 50 m spatial resolution, the calculated coherent Rayleigh noise was 4.4%. In the case of the proposed WTOTDR (The linewidth of laser is about 0.11 nm), the theoretical coherent Rayleigh noise using above equation was 0.89%. From this result, we could expect that the variation of the coherent Rayleigh noise can be effectively reduced. We set the repetition rate to 5 kHz and we could expect that the variation of the coherent Rayleigh noise using above equation was 0.89%. From this result, we could expect that the variation of the coherent Rayleigh noise can be effectively reduced. We set the repetition rate to 5 kHz and pulse width to 0.2 \( \mu s \) to achieve the spatial resolution of 20 m. The measured backward reflection traces of WTOTDR at each wavelength were shown in Fig. 7. In each trace, attenuations or Fresnel reflections from splicing point, connector connection point, and PC connector at the end of each fiber branch were clearly observed. The calculated fault distances were 24.99, 4.75, 20.7, and 25.69 km from the output node of AWG, respectively. These fault positions accurately match to the real length of the drop fibers. The dynamic range of measured on the OTDR trace was more than 18 dB for 0.5 \( \mu s \) probe pulse. The measured spatial resolution was about 20 m. This spatial resolution of the realized WTOTDR fully satisfies to detect fault location in metro and access networks.

4. Conclusion

We have demonstrated flexible fiber-fault location detecting technique with WTOTDR. By fully utilizing the DMD based swept fiber laser and COTDR technique, WTOTDR was realized with a spatial resolution of 20 m and a fast wavelength setting speed of \(~15\) \( \mu s \). The realized cost effective WTOTDR has a wide tuning range of \(~40\) nm in C-band, dynamic range of more than 18 dB and confirms strong potential to the application in optical tests and measurements. The proposed fiber-fault location detecting technique would be well suited for dynamically on-line monitoring the status of not only the access network but also the metro network.

Acknowledgements

This work was partially supported by Ministry of Education, Science and Technology of Korea through APRI-Research Program of GIST.

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