광통신 시스템에서의 색분산 모니터링과 운용 기술의 현황

Status of Chromatic Dispersion Monitoring and Management Techniques in Fiber Communication Systems

이병호
서울대학교 전기 · 컴퓨터공학부
byoungho@snu.ac.kr

색분산은 주파수가 다른 빛이 광섬유 내에서 서로 다른 속도로 진행하는 현상으로서, 광섬유를 통해 진행하는 광 신호의 시간 축에서의 확산을 일으키는 가장 큰 요인이다. 광 신호의 단일 펄스 내에 존재하는 광자들은 서로 약간씩 다른 주파수를 가지므로, 전송 거리가 커질수록 색분산에 의해 펄스폭이 넓어진다. 광 신호의 비트율이 증가할수록 펄스의 주파수 범위가 넓어지므로 색분산에 의한 영향은 증가하게 된다. 또한, 비트율의 증가는 광 펄스간의 시간 간격을 좁히므로 인접 펄스와 겹쳐지지 않는 범위에서 허용되는 신호의 확산 한도는 비트율에 반비례하여 줄어든다. 따라서 색분산에 의한 전송 거리의 한계는 비트율 증가의 제곱에 반비례하여 줄어든다.[1,2] 이와 같은 색분산의 영향은 분산이 0이 되도록 설계된 광섬유를 사용하면 제거할 수 있다. 그러나 파장 분할 다중화(WDM) 시스템에서 분산이 영인 광섬유를 사용하면 여러 파장의 빛이 시공간적으로 중첩된 상태로 진행하게 되어 신호에 왜곡을 주는 비선형 효과가 쉽게 나타날 수 있다. 따라서 WDM 시스템에서 색분산을 다루는 핵심은 색분산을 제거하는 것이 아니라 적정 수준에서 값을 조절하는 것이다. 이와 같이 전송로를 따라 누적되는 색분산의 양을 적절히 조절하는 것을 색분산 운용(chromatic dispersion management)이라고 한다. 색분산 운용의 효과적인 방법으로 분산 지도(dispersion map)를 만드는 방법이 있다. 분산 지도는 전송로를 따라 양의 분산과 음의 분산을 반복적으로 겪도록 하여 전체 누적 색분산은 0이 되게 하면서, 각 부분에서의 분산 값은 비선형 효과를 줄일 수 있는 적정한 값이 유지되게 하는 것이다.

효과적인 색분산 운용을 위해서는 전송로의 색분산과 분산 보상기의 색분산을 정밀하게 측정하는 것이 필요하다. 색분산의 측정은 보통 전송로나 소자가 신호를 전송하지 않는 상태에서 측정하는 것을 말한다. 분산 측정의 대표적인 방법은 변조 위상 천이 방법(modulation phase shift method)으로 대부분의 상용화된 분산 측정기에서 사용하고 있다. 색분산 측정과는 반대로, 신호가 전송되고 있을 때 실시간으로 발생하는 색분산 값을 읽어내는 것을 분산 모니터링이라고 한다. 분산 모니터링은 신호의 수광부에서 읽혀진 신호의 Q값, eye diagram, 또는 BER을 분석함으로서 누적된 색분산의 양을 계산하게 된다. 색분산의 모니터링은 실시간으로 변화하는 분산 값을 읽어낼 수 있으므로, 피드백 콘트롤을 통한 동적 색분산 보상에 사용될 수 있다. 표 1은 색분산의 측정과 모니터링 방법을 분류하고 이에 대한 대표적인 참고문헌을 정리한 것이다.

지금까지의 색분산 보상은 주로 음의 분산 값을 갖는 분산 보상 광섬유(dispersion compensation fiber: DCF)를 전송로의 중간에 삽입하는 식으로 이루어져 왔다. 그러나 DCF는 효과적(effective) 코어 반경이 일반 단일모드 광섬유에 비해 작아서 비선형 효과가 쉽게 발생하고, 동적으로 변하는 분산에 대해서는 효과적으로 대응 할 수 없다는 단점이 있다. 그래서 DCF의 문제점을 개선하는 연구들과 함께, DCF를 대체할 수 있는 처핑된 광섬유 격자(chirped fiber Bragg grating: CFBG), VIPA(virtually imaged phased array), 간섭계, all-pass-filter 등을 이용한 분산 보상 소자에 대한 연구가 활발하게 진행되어 왔다. 표 2는 색분산 경감 기술의 종류를 분류하고 각각의 대표적인 연구 논문들을 정리한 것이다. 분산 보상 기술들 중에 현재 제품으로 상용화된 기술로는 DCF, CFBG, Gires-Tournois etalon를 이용한 것 등이 있다. 또한, CFBG나 etalon을 이용한 제품은 동적 분산 보상용 제품도 판매되고 있다.

표 1. 색분산 측정 및 모니터링 방법과 대표적인 연구 사례

분류	방법	대표적 참고문헌
색분산 측정	General	L. G. Cohen, "Comparison of single-mode fiber dispersion measurement techniques," Journal of Lightwave Technology, vol. LT-3, no. 5, pp. 958-966, Oct. 1985.
	The modulation phase shift method	B. Costa, D. Mazzoni, M. Puleo, and E. Vezzoni, "Phase shift technique for the measurement of chromatic dispersion in optical fibers using LED's," IEEE Journal of Quantum Electronics, vol. QE-18, no. 10, pp. 1509-1515, Oct. 1982. R. Fortenberry, W. V. Sorin, and P. Hernday, "Improvement of group delay measurement accuracy using a two-frequency modulation phase-shift method," IEEE Photonics Technology Letters, vol. 15, no. 5, pp. 736-738, May 2003.
	The baseband AM response method	B. Christensen, J. Mark, G. Jacobsen, and E. Bdtker, "Simple dispersion measurement technique with high resolution," Electronics Letters, vol. 29, no. 1, pp. 132-134, Jan. 7, 1993.
	Interferometric method	K. S. Abedin, M. Hyodo, and N. Onodera, "Measurement of the chromatic dispersion of an optical fiber by use of a Sagnac interferometer employing asymmetric modulation," Optics Letters, vol. 25, no. 5, pp. 299-301, Mar. 1, 2000.
색분산 모니터링	PM-AM conversion method	M. Tomizawa, A. Sano, Y. Yamabayashi, and K. Hagimoto, "Automatic dispersion equalization for installing high-speed optical transmission systems," Journal of Lightwave Technology, vol. 16, no. 2, pp. 184-191, Feb. 1998.
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	NRZ clock regeneration and RZ clock fading method	Z. Pan, Q. Yu, Y. Xie, S. A. Havstad, A. E. Willner, D. S. Starodubov, and J. Feinberg, "Chromatic dispersion monitoring and automated compensation for NRZ and RZ data using clock regeneration and fading without adding signaling," Optical Fiber Communication Conference, vol. 3, pp. WH5_1-WH5_3, 2001. A. Sano, Y. Miyamoto, T. Kataoka, M. Tomizawa, and K. Hagimoto, "Extracted-clock power level monitoring scheme for automatic dispersion equalization in high-speed optical transmission systems," IEICE Trans. Commun., vol. E84-B, no. 11, pp. 2907-2914, Nov. 2001.
	Phase shift between two WDM channels method	A. Sano, Y. Miyamoto, S. Kuwahara, and H. Toba, "Adaptive dispersion equalization by monitoring relative phase shift between spacing-fixed WDW signals," Journal of Lightwave Technology, vol. 19, no. 3, pp. 336-344, March 2001
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표 2. 색분산 경감 기술과 대표적인 연구 사례

기술 분류	대표적 참고문헌
Dispersion shifted and compensation fibers	C. Lin, H. Kogelnik, and L. G. Cohen, "Optical-pulse equalization of low-dispersion transmission in single-mode fibers in the 1.3-1.7-μm spectral region," Optics Letters, vol. 5, no. 11, pp. 476-478, Nov. 1980. A. J. Antos and D. K. Smith, "Design and characterization of dispersion compensating fiber based on the LP01 mode" Journal of Lightwave Technology, vol. 12, no. 10, pp. 1739-1745, Oct. 1994. M. Eiselt, L. D. Garrett, and R. W. Tkach, "Experimental comparison of WDM system capacity in conventional and nonzero dispersion-shifted fiber," IEEE Photonics Technology Letters, vol. 11, no. 2, pp. 281-283, Feb. 1999. T. Yamamoto, E. Yoshida, K. R. Tamura, K. Yonenaga, and M. Nakazawa, "640-Gbit/s optical TDM transmission over 92 km through a dispersion-managed fiber consisting of single-mode fiber and "reverse dispersion fiber"," IEEE Photonics Technology Letters, vol. 12, no. 3, pp. 353-355, Mar. 2000. L. Gruner-Nielsen, S. N. Knudsen, B. Edvold, T. Veng, D. Magnussen, C. C. Larsen, and H. Damsgaard, "Dispersion compensating fibers," Optical Fiber Technology, vol. 6, pp. 164-180, 2000. P. Nouchi, L.-A. de Montmorillon, P. Sillard, A. Bertaina, and P. Guenot, "Optical fiber design for wavelength-multiplexed transmission," Comptes Rendus Physique, vol. 4, pp. 29-39, 2003.
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