Experimental investigation of the relationship between inter-core crosstalk and Q-factor in multicore DSDM transmission lines

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\textbf{Abstract:} We demonstrate the relationship between inter-core crosstalk and Q-factor in a multicore transmission line including a multicore fiber and a multicore amplifier by using an in-service inter-core crosstalk monitoring method we propose. The method estimates inter-core crosstalk by using tones with different wavelengths for each core. We measured Q-factors at the center wavelength of the WDM channel. The measured crosstalk was $-20.2\, \text{dB}$ and the Q-factor was $5.8\, \text{dB}$ after 411.2-km transmission. The Q-factor estimated from the monitored crosstalk was found to closely match the measured value.

\textbf{Keywords:} space division multiplexing (SDM), dense SDM (DSDM), multicore fiber (MCF), crosstalk (XT), crosstalk monitoring

\textbf{Classification:} Fiber-Optic Transmission for Communications

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1 Introduction

Space division multiplexing (SDM) for optical fiber transmission is one of the breakthrough techniques in overcoming the capacity limit of single-mode fiber [1]. SDM transmission uses a multicore arrangement of many cores in one fiber and/or a few-mode core with large-diameter cores, each of which can carry many optical modes. The characteristics of these fibers can yield very high capacity transmission systems. We refer to Dense SDM (DSDM) as SDM with over 30 spatial channels. The merit of DSDM transmission systems is achieving very high capacity transmission. Given the importance of higher-capacity transmission, many researchers have reported DSDM transmission experiments [2]. We focused on multicore DSDM transmission because it is a natural extension of the current optical transport network. A key issue in multicore DSDM transmission systems is inter-core crosstalk (XT), which refers to optical signals leaking from one core to another and is likely to degrade transmission quality. It is therefore necessary to avoid XT effects in transmission signals through optical paths. One way to do this is to change the modulation format and/or optical path by monitoring XT values at each point in multicore DSDM transmission systems. To achieve XT-aware network control, it is important to measure XT accurately.

This paper demonstrates the relationship between XT and Q-factor by using our in-service inter-core XT monitoring method in a DSDM transmission line that includes a 32-core MCF [3] and a 32-core multicore erbium/ytterbium-doped optical fiber amplifier (MC-EYDFA) [4].

2 Crosstalk monitoring method

Fig. 1 shows the concept of the XT monitoring method we previously proposed [5]. This method uses tones that have different wavelengths in different cores. For example, in the case shown in Fig. 1, we input WDM 1 ($\lambda_1, \lambda_2, \lambda_3$) and WDM 2 ($\lambda_2, \lambda_3$) signals and four pilot tones into a 2-core transmission line. The tones are used to estimate the XT between cores. Pilot tones $\lambda_{MIS}$ and $\lambda_{MIL}$ are added to the WDM1 signal of the core #1 (core under test) by optical couplers. The power of
pilot tones $\lambda_{\text{M1S}}$ and $\lambda_{\text{M1L}}$ are set at the same level of WDM1’s power. In a like manner, WDM2 signals in the core #2 (adjacent core) are overlaid by pilot tones $\lambda_{\text{M2S}}$ and $\lambda_{\text{M2L}}$. The power of pilot tones $\lambda_{\text{M2S}}$ and $\lambda_{\text{M2L}}$ are also set at the same level of WDM2’s power. In the multicore transmission line, signals are affected by inter-core crosstalk. At the end of the transmission line, the spectrum from core #1 has tones $\lambda_{\text{M1S}}$, $\lambda_{\text{M1L}}$, WDM1, and XT of tones $\lambda_{\text{M2S}}$ and $\lambda_{\text{M2L}}$. Conventionally, we could not measure the XT value of the WDM signals from core #2 to core #1 because WDM2 will overlap with WDM1. But with our method, we calculated the XT as follows. First, we regarded the shorter-wavelength side XT at $(\lambda_{\text{M1S}} + \lambda_{\text{M2S}})/2$ as the difference in the peak power between $\lambda_{\text{M1S}}$ and $\lambda_{\text{M2S}}$, and the longer-wavelength side XT at $(\lambda_{\text{M1L}} + \lambda_{\text{M2L}})/2$ as the difference in the peak power between $\lambda_{\text{M1L}}$ and $\lambda_{\text{M2L}}$. Next, assuming that inter-core XT is a linear function of wavelength, we used linear approximation to estimate XT at each WDM channel using the shorter and longer-wavelength side XT values. This method is suitable for use under the condition that the OSNR level is higher than the XT value, and may affect the accuracy when the tones from neighboring cores are near the noise level [5].

Our XT monitoring method has three merits. The first is that it needs no additional signal frames for XT monitoring, because pilot tones are used. The second is that in-service monitoring is possible even in a multicore transmission line that includes optical amplifiers. The third is that we need only two pilot tones per core to monitor XT of the WDM channels, and by placing them out of the WDM signals, it will not affect spectral efficiency. These merits make it very easy and practical for in-service XT monitoring.

**3 Experimental setup**

We conducted an experiment on a 32-core DSDM transmission line to confirm the accuracy of our crosstalk monitoring method. Fig. 2 shows the experimental setup.
We used a 51.4-km 32-core MCF [3] and a 32-core MC-EYDFA with a 32-core multicore isolator [6] as a single span transmission line. Cores #1, #3, #7, #9, #15, #23, #27 and #31 were connected in series to yield an 8-span MCF transmission line (Fig. 2(c)). Signals were input to the remaining 24 cores to assess the effects of XT from adjacent cores. The WDM signals we used were 32-Gbaud polarization division multiplexed 16 quadrature amplitude modulation (PDM-16QAM) 50 GHz-grid 27WDM (1551.520 nm–1562.029 nm) and the Q-factors at the center wavelength of the WDM channel (1556.756 nm) were measured. The WDM signals were divided by 1×2 optical couplers for input to the core under test and to adjacent cores. Pilot tones $\lambda_{\text{M1S}}$ (1550.717 nm) and $\lambda_{\text{M1L}}$ (1562.436 nm) from laser diodes (LDs) for the core under test and WDM signals from the transmitter were coupled by using 2×1 optical couplers, then input to the core under test. Pilot tones $\lambda_{\text{M2S}}$ (1551.119 nm) and $\lambda_{\text{M2L}}$ (1562.844 nm) from LDs for the adjacent cores and WDM signals from the transmitter were coupled by using 2×1 optical couplers, then input to the adjacent cores by using a 1×32 optical coupler. Delay lines were set after the 1×32 optical coupler to decorrelate the signals between adjacent cores. After transmission in the core under test, the WDM signals and the pilot tones were sent to the receiver and the optical spectrum analyzer by using a 1×2 optical coupler. At the receiver, we measured the Q-factor at 1556.756 nm by offline processing. At the optical spectrum analyzer, we estimated the XT value from the optical peak power of each wavelength by determining the optical power ratios of $\lambda_{\text{M1S}}$, $\lambda_{\text{M1L}}$, $\lambda_{\text{M2S}}$, and $\lambda_{\text{M2L}}$. The resolution of optical spectrum analyzer is 0.1 nm. In this experiment, we measured Q-factors and XT from 51.4 km to 411.2 km for each 51.4-km span to reconnect cores in series. When we measured XT and Q-factor at 2 spans, we connected cores #1 and #3 in series as the core under test, and the 30 other cores were connected via the 1×32 optical coupler as in Fig. 2.

![Fig. 2.](image-url)
adjacent cores. In the same way, when we measured XT and Q-factor at 4 spans, we
connected cores #1, #3, #7, #9 in series as the core under test, and the 28 other
cores were connected via the 1 × 32 optical coupler as adjacent cores. We changed
the number of adjacent cores in accordance with the number of spans for the
serially-connected transmission line.

4 Experimental results

To examine the relationship between XT and Q-penalty, we estimated Q-factors
from the calculated Q-penalty by using the XT value monitored at each 51.4-km
transmission span. Fig. 3 plots monitored XT and measured Q-factor values at
1556.756 nm. XT values are given by the green solid line with a triangular marker.
They increased with transmission distance. The XT value was −20.2 dB and the
measured Q-factor (see the blue solid line with quadrangular marker) was 5.8 dB
after 411.2-km transmission. This value indicates the possibility of transmitting
C-band WDM signals using a PDM-16QAM modulation format over 411.2 km in a
32-core DSDM transmission line. Estimated Q-factors at each distance are plotted
by pink dotted lines and noted as “Q-factor (estimated)” in Fig. 3. We evaluated the
estimated Q-factor at each distance as follows. First, we needed OSNR without XT
to calculate Q-factors at each distance. Since we set the pilot tones and WDM
signals to have the same power, we regarded the difference between the peak power
of the pilot tone from the core under test and the power level of the noise floor
as OSNR. We called Q-factors that had no Q-penalty induced by XT Q-factors and calculated them at each distance from the OSNR and back-to-back
OSNR. Finally, we added the Q-penalty induced by XT to the non-XT Q-factors at
each distance and regarded them as estimated Q-factors [7]. When we compared the
measured and estimated Q-factors at each distance, we found that there was only a
small discrepancy between them. That is, it ranged from only −0.3 dB to +0.5 dB.
This confirms that our XT monitoring method is effective in measuring inter-core
XT in service.

![Graph](image-url)

Fig. 3. Measured crosstalk and Q-factors as a function of transmission
distance
5 Conclusions

We experimentally demonstrated the relationship between XT and Q-factor in a 32-core DSDM transmission line. At 1556.756 nm after 411.2-km transmission the measured XT was $-20.2$ dB and the Q-factor was 5.8 dB. A comparison of measured and estimated Q-factors at multiple spans showed that they were virtually the same value. This means our XT monitoring method will be effective in confirming the quality of transmission signals in service, and that it will also be useful as a means to provide XT-aware optical channel control.

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