Laser Frequency Control Using Kalman-filter-based Q-factor Estimation for Extreme WSS Passband Narrowing with Minimum Frequency Grid

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***Abstract*— We proposed a frequency control using a Kalman filter-based estimation for Nyquist DP-16QAM transmission with frequency drift in the ROADM system with a WSS passband of 12.5 GHz. Dynamic characteristics by simulation showed stable operation.**

Keywords— ROADM, Frequency tuning, Kalman filter

I. INTRODUCTION

Demand for optical transport network (OTN) systems that perform route selection according to optical wavelength paths based on the wavelength division multiplexing (WDM) method will continue in the future to efficiently accommodate diverse IoT traffic over optical fibers [1]. In the OTN system, it is necessary to allocate wavelengths flexibly. Fine-grained switching in the wavelength domain is required for optical transceivers and repeaters in reconfigurable optical add-drop multiplexer (ROADM) nodes [2]. All-optical processing within the optical nodes has recently been investigated for an all-optical network from the optical access network to the metro network [3].

A wavelength-selective switch (WSS) is placed in the ROADM node of the OTN system to switch paths according to wavelength. The transmission band of WSS varies discretely with a granularity of 12.5 GHz [4]. In general, the transmission spectrum of WSS has a flat component with sufficiently constant transmission intensity as the number of grids used increases. However, at the smallest frequency grid width, equivalent to 12.5 GHz, the transmission spectrum has a low-order Gaussian shape with few flat components [5]. Therefore, the effect of signal bandwidth narrowing caused by passing through multiple ROADM nodes increases compared to broadband transmission characteristics using multiple grid widths [6]. When it is set to 12.5 GSymbol/s, corresponding to WSS's minimum wavelength grid width, it is necessary to consider the effect of band narrowing by WSS carefully. In addition, the drift of the optical frequency of the transmission light source in the optical transceiver due to long-term operation [7] causes excessive signal quality degradation due to the band narrowing of the WSS, so high-precision optical frequency control of the transmission light source is required.

In this paper, we proposed light source frequency control using signal quality estimation by Kalman filter with minimum grid width where band narrowing is remarkable in WSS in the ROADM node. We evaluated dynamic characteristics by the simulation to confirm the control operation. When the training samples used for the Kalman filter are sufficiently short for the time required for the long-term fluctuation of the light source frequency, the operation is confirmed by applying the linear Kalman filter on the optical receiver side.

II. PRINCIPLE OF OPTICAL FREQUENCY CONTROL USING KALMAN FILTER

The proposed optical frequency control method calculates the estimated Q-factor using a Kalman filter based on the past received Q-factor over the ROADM system. The controller detunes the optical frequency of the transmission light source. Based on the Q-factor obtained from the system model, it is necessary to convert it to the estimated optical frequency drift value F_{est}, which is the estimated value of the Kalman filter in the control model and feed it back to the system model. In this system, we assume an optical frequency drift of up to 1.5 GHz. If the total number of samples in the observation time is K, a linear optical frequency fluctuation of $1.5/K$ GHz/sample occurs in one sample.

After estimating the deterioration of the Q-factor in advance using a Kalman filter, loop control is performed for each sample to convert it into optical frequency fluctuation as a physical quantity. Optical frequency control uses N past learning samples to calculate the estimated Q-factor with a Kalman filter. Since the polarity of the frequency at the time of optical frequency drift cannot be determined by a spectrum monitor, etc., the polarity of the optical frequency control is reversed when the amount of Q-factor degradation falls below the set threshold due to an error in the polarity of the optical frequency control, as shown in Fig. 1.

Figure 2 shows the flow of optical frequency control using a Kalman filter when the polarity of the optical frequency drift of the transmission light source is unknown. The sample number at the time of processing is k, and in the

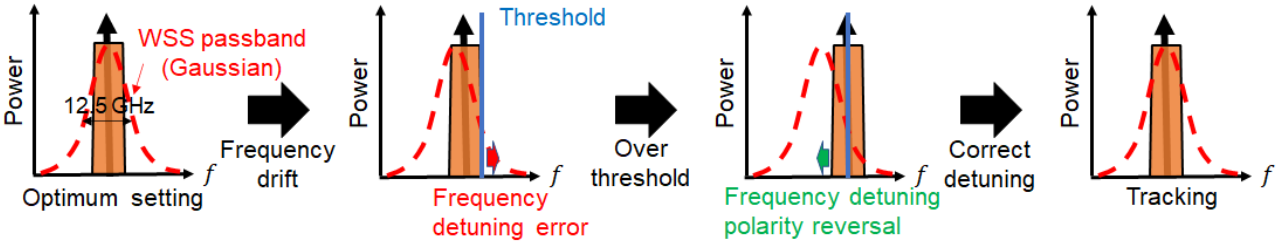

Fig. 1. Wrong polarity frequency detuning situation for frequency drift.

Kalman filter, $Q(k)$ at k is the plant input $y_v(k)$, and the amount of Q-factor degradation is estimated.

$$y_v\ (k) = Q\ (k) \tag{1}$$

$$y_v\ (k) = y_v\ (k) - y_v\ (1) \tag{2}$$

In the optical frequency control using the Kalman filter, the pre-estimated value $\hat{x}[k|k]$ is first estimated based on the Q-factor for the number of training samples. After that, the estimated Q-factor degradation $\hat{x}[k+1|k]$ due to the deviation from the optimal optical frequency allocation is output from the pre-estimated value and the system noise $v[k]$.

$$\hat{x}[k|k] = \hat{x}[k|k-1] + g(y_v(k) - C\hat{x}[k|k-1]) \tag{3}$$

$$\hat{x}[k+1|k] = A\hat{x}[k|k] + Bv[k] \tag{4}$$

The following equation can express the frequency fluctuation F_{shift} without optical frequency control.

$$F_{shift}(k) = \frac{1.5\times10^9}{1200}\times k \tag{5}$$

Here, we explain the relationship between Q-factor degradation and optical frequency fluctuation. When the central optical frequency variation of the light source is 1.5 GHz at maximum, the Q-factor degradation in the ROADM system with two stages of WSS is about 1.5 dB. Based on this relationship, the following equation expresses the control value F_{est} obtained from the estimated Q-factor degradation ye (k).

$$F_{est}\ (k) = \hat{x}[k+1|k]\times10^9 \tag{6}$$

In other words, if the amount of optical frequency detuning of the light source is F_v, the optical frequency fluctuation of $F_v = F_{shift}$ occurs before the start of control. Still, it can be reduced to the following frequency fluctuation using the estimated value of the Kalman filter during the control time. However, the frequency drift of the transmitting light source is assumed to be in the positive direction.

$$F_v\ (k) = F_v\ (k-1) - F_{est}(k) \tag{7}$$

When the Q-factor degradation falls below the threshold due to a polarity error in optical frequency control and the optical frequency drift direction of the transmission light source is estimated to be in the negative direction, the optical frequency detuning amount of the light source is changed as follows.

$$F_v(k) = F_v(k-1) + F_{est}(k) \tag{8}$$

III. Simulation Model

Figure 3 shows a simulation model of a ROADM system in which control using a Kalman filter is applied to the DSP on the optical receiver side. The DSP on the optical transmitter side performs optical spectrum shaping with a root-raised cosine filter (RRCF) and then inputs the light source (LD) output to the DP-IQ modulator to generate a DP-16QAM

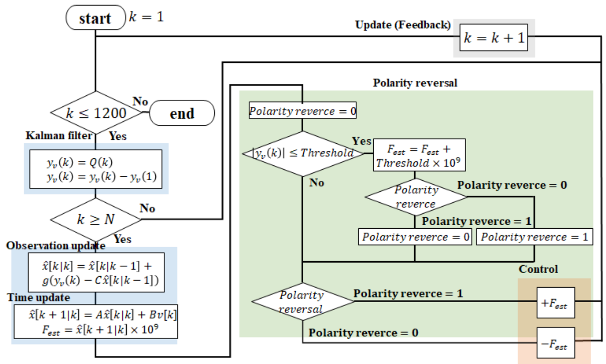

Fig. 2. Flow of frequency control using Kalman filter with threshold.

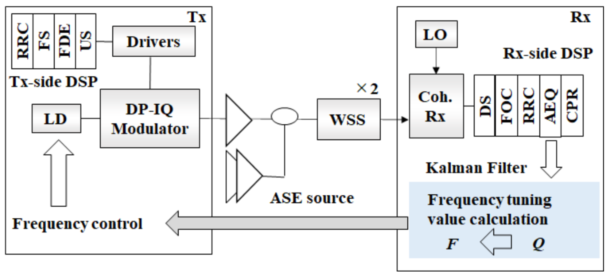

Fig. 3. Simulation setup.

signal. Phase noise and frequency variation are added to each sample of the DP-16QAM signal. In the transmission line, amplified spontaneous emission (ASE) is added as noise, and band narrowing is provided by two-stage WSS with a Gaussian-shaped transmission band. The received signal is coherently detected simultaneously as the local oscillator light (LO). At the receiver-side DSP, frequency offset compensation (FOC), RRC, adaptive equalizer (AEQ), and carrier phase recovery (CPR) are performed. After equalization processing by DSP, the Q-factor is calculated from the signal affected by passband narrowing and optical frequency fluctuation.

TABLE I Simulation Parameters

Parameter		Value
Transmission distance [km]		20
Symbol rate [Gsymbol/s]		12.5
Sample rate [Gsymbol/s]		100
RRCF roll off factor		0.05
Phase offset [rad]		π/4
Frequency offset [GHz]		1
Frequency resolution [Hz]		10000
Normalized loop bandwidth		2×10^{-4}
Threshold of polarity reversal [dB]		5.4
AEQ	Number of taps	7
	Step size	2.5×10^{-6}

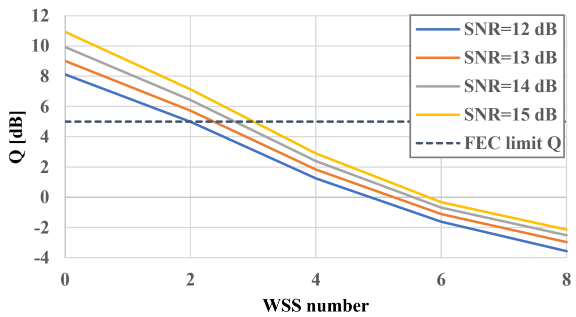

Fig. 4. Q-factor for the number of WSS stages.

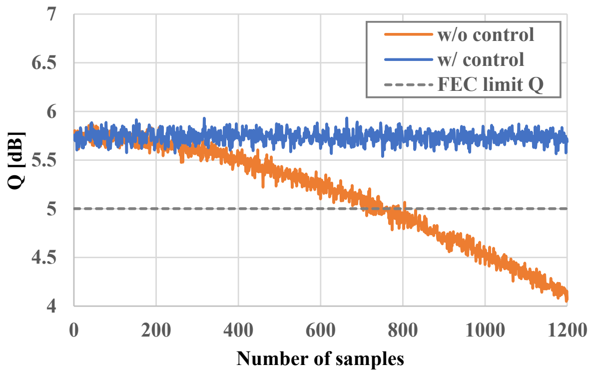

Fig. 5. Dynamic Q-factors during frequency detuning without polarity error.

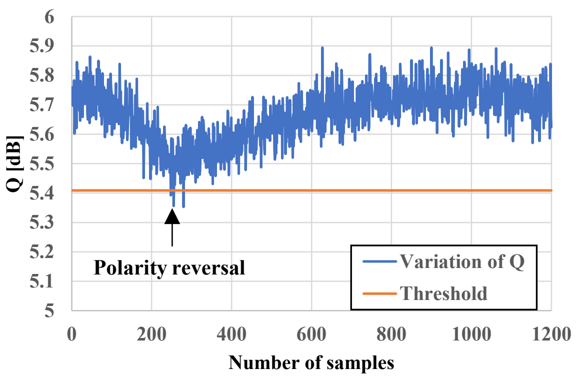

Fig. 6. Dynamic Q-factors during frequency detuning with polarity error.

Table 1 shows the setting parameters in the simulation. The Q-factor of the forward error correction (FEC) limit, when converting the bit error ratio (BER) into a Q-factor and evaluating it, is assumed to be 5 dB. The Kalman filter inputs the Q obtained from the DP-16QAM signal on the optical receiver side as the observed value and uses the state space model transformed from the transfer function. In addition, the Q obtained from the Kalman filter gets an observed value every second considering the transmission delay time required for feedback from the optical receiver to the optical transmitter side.

IV. Simulation Results

Figure 4 shows the number of WSS stages versus Q in the DP-16QAM signal. Since the effect of band narrowing is extremely large at the point of 2-stage WSS, the dynamic characteristic shows the Q fluctuation when applying control by a Kalman filter to a DP-16QAM signal with SNR = 13 dB with 2-stage WSS. The number of training samples during control was set to 10, compared with dynamic characteristics without control.

Figure 5 shows the dynamic characteristics of the Q-factor at frequency detuning without polarity error. We confirmed that the degradation estimation of the Q-factor and the optical frequency control by the Kalman filter are possible. In addition, the Q-factor is maintained almost constant. We can secure the same system stability as when optical frequency drift does not occur.

Figure 6 shows the dynamic characteristics of the Q at frequency detuning with polarity error. In contrast to the monotonous degradation of the Q in the region above the threshold at the start of control, the Q is stable due to the accurate compensation of the optical frequency drift from the threshold. In other words, even if the optical frequency drift and the polarity of the optical frequency control cannot be calculated, the Q estimation and the optical frequency control using the Kalman filter are possible.

V. Conclusions

To suppress the signal characteristic deterioration when the center optical frequency drift of the transmission light source occurs in the situation of extreme passband narrowing corresponding to one grid of WSS in the ROADM system, we proposed a new frequency control method using the signal quality estimation by the Kalman filter, using the Q obtained by the optical receiver side DSP as the monitor signal. Regardless of the polarity of the frequency drift of the light source, we estimated the deterioration of the signal quality due to the optical frequency drift from the initial stage and showed that we could prevent significant damage to the Q-factor by controlling the optical frequency.

Acknowledgment

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