Optimum 10-Gb/s NRZ Receiver Bandwidths for Ultradense WDM Transmission Systems

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***Abstract*—This letter reports the results of an experimental and numerical simulation study on optimum 10-Gb/s nonreturn-to-zero receiver bandwidths for ultradense wavelength-division-multiplexing (UDWDM) transmission systems. It is found that as channel spacing is scaled down to UDWDM dimensions from 50 to 25 GHz, the optimum receiver bandwidth increases. Moreover, an UDWDM system with 25-GHz channel spacing offers the opportunity to improve receiver performance by taking advantage of the optical matched filter concept. A 25-GHz channel spacing optical filter, designed to approach the performance of an optical matched filter, shows a ∼1.3 dB*Q* advantage compared to a 50-GHz channel spacing optical filter when receiver bandwidth is optimized.**

***Index Terms*—DWDM, matched filters, optical filters, receivers.**

I. INTRODUCTION

As FIBER-OPTIC transmission systems scale to ultradense wavelength-division-multiplexing (UDWDM) dimensions of 25-GHz channel spacing, the relationship between the optical demultiplexing filter and receiver electrooptic frequency response becomes increasingly important. One of the most important parameters in this relationship is the receiver bandwidth in comparison to the optical filter bandwidth [1]. The optical filter bandwidths in UDWDM systems, by necessity, approach a 10-Gb/s nonreturn-to-zero (NRZ) signal bandwidth in order to provide the required cross-talk isolation. Thus, if an UDWDM optical filter is used in conjunction with a 10-Gb/s NRZ receiver, typically designed with ∼7-GHz bandwidth, over filtering of the signal will result. This may give the appearance that an UDWDM system must suffer an inherent penalty due to the narrow optical demultiplexing filter when compared to wider channel spacing systems. However, it is well known that an optical filter with bandwidth comparable to the signal may be designed to function as an optical matched filter [2]–[4]. An optical matched filter provides a compromise between amplified spontaneous emission (ASE) noise rejection and eye closure due to filtering. In practice, the filter bandwidth is one among other parameters optimized in matched filter design [2]. A recent simulation study demonstrates that the optimum optical filter bandwidth for an ASE-limited 10-Gb/s NRZ signal is 14 GHz, when the receiver bandwidth is also optimized [5]. It would be useful to substantiate these interesting modeling results with experimental data.

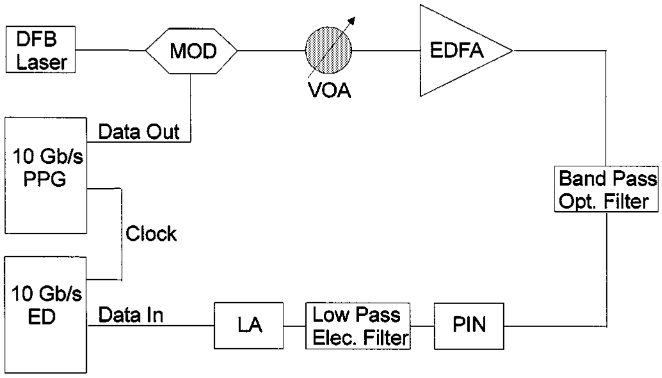

Fig. 1. Schematic diagram of experimental setup for a back-to-back ASE noise loaded measurements.

In this letter, we investigate the relationship between the optical filter and receiver bandwidths for 10-Gb/s NRZ signals through an experimental and numerical simulation study. This work complements a recently reported experimental study of optimum NRZ receiver bandwidths at a lower data rate of 3.5 Gb/s [6]. Our experiments demonstrate that a properly designed 25-GHz channel spacing UDWDM optical filter-receiver pair may result in as much as ∼1.3-dB*Q* improvement over a conventional 50-GHz channel spacing DWDM optical filter-receiver. The simulations show that, in addition to optimizing receiver bandwidth, it is also important to optimize the shape of the receiver electrooptic response.

II. EXPERIMENT DESCRIPTION

Fig. 1 shows a schematic diagram of the experimental setup, designed for back-to-back ASE noise loaded measurements. The transmitter consists of a distributed-feedback (DFB) laser followed by a zero-chirp Lithium Niobate modulator. The modulator is modulated by a 10-Gb/s NRZ data signal generated by a pulse pattern generator (PPG). The PPG is set for generating a $2^{23}-1$ pseudorandom binary sequence (PRBS) data signal. A variable optical attenuator (VOA) controls the optical power level at the output of the modulator. After the VOA, the optical signal goes through an erbium-doped fiber amplifier (EDFA). The input power into the EDFA is set using the VOA to obtain an output signal with optical signal-to-noise ratio (OSNR) equal to 17 dB. The OSNR is measured with 0.1-nm resolution, and includes both polarization modes. Setting the OSNR to 17 dB ensures that the dominant noise source at the receiver is due to ASE from the EDFA. Such a low OSNR at the receiver

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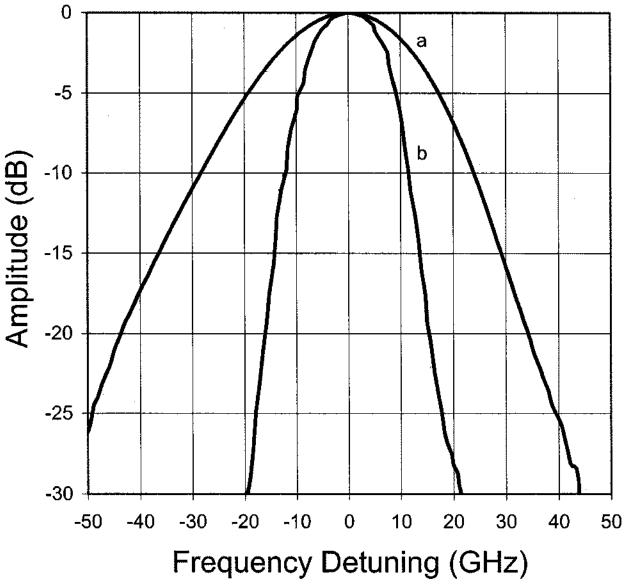

Fig. 2. Measured optical bandpass filter amplitude response versus frequency detuning for (a) JDSU TB9 filter with 28-GHz bandwidth, designed for 50-GHz channel spacing measurements. (b) FBG filter with 16-GHz bandwidth, designed for 25-GHz channel spacing UDWDM.

is typical for long-haul DWDM transmission systems utilizing forward error correction.

The optical signal and associated ASE noise output from the EDFA is passed through an optical bandpass filter. Fig. 2 shows the amplitude response of the two optical bandpass filters used in the experiment. Curve "a" shows the amplitude response of a JDSU TB9 filter with 28-GHz bandwidth. The TB9 optical filter represents the performance of a typical 50-GHz channel spacing DWDM demultiplexing filter. Curve "b" shows the amplitude response of a fiber Bragg grating (FBG) filter with 16-GHz bandwidth. The FBG filter bandwidth is close to the optimum for 10-Gb/s NRZ signals [5]. The FBG filter shape is designed for 25-GHz channel spacing UDWDM by optimizing the tradeoff between cross talk and dispersion [7], [8]. Although the UDWDM FBG is not a perfectly matched filter, it approximates a matched filter much better compared to the TB9. Thus, we expect to see a performance advantage when employing the UDWDM FBG filter in an ASE noise dominated system.

After passing through the optical bandpass filter, the signal is received by a p-i-n with 15-GHz bandwidth. The p-i-n is followed by a selectable RF low-pass filter, a limiting amplifier (LA), and an error detector. The decision threshold at the input to the LA, as well as error detector threshold, and sampling instant are all optimized before measuring bit error rate (BER).

The receiver bandwidth is varied in the experiment by using different RF low-pass filters. Fig. 3 shows the electrooptic response (S21) of the receiver, including RF filter and LA, for several different RF filters. The S21 is measured using an HP vector network analyzer, where the optical probe signal power was set low enough to ensure linear operation of the LA. The 3-dB receiver bandwidth is estimated from the measured S21 data fitted with a smooth polynomial. Thus, the five RF low-pass filter combinations allow measurements with receiver bandwidths of 5.5, 5.8, 7.0, 8.0, and 9.7 GHz.

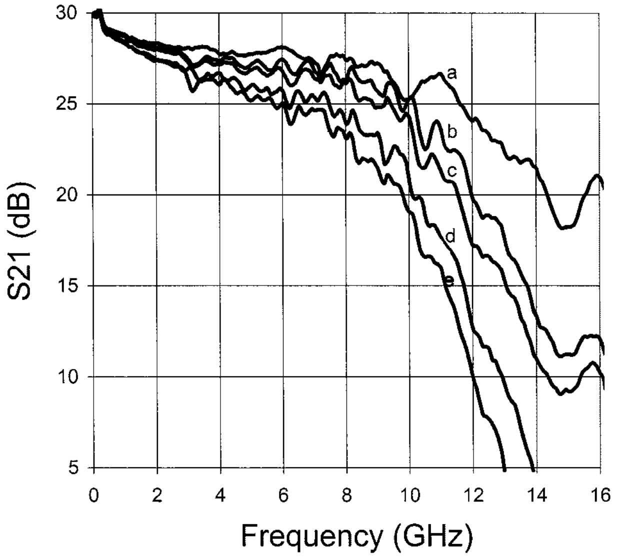

Fig. 3. Measured receiver electrooptic response (S21) using various RF low-pass filter combinations. (a) No filter. (b) 10-GHz filter. (c) 7.5-GHz filter. (d) 10- and 7.5-GHz filters in series. (e) Two 7.5-GHz filters in series.

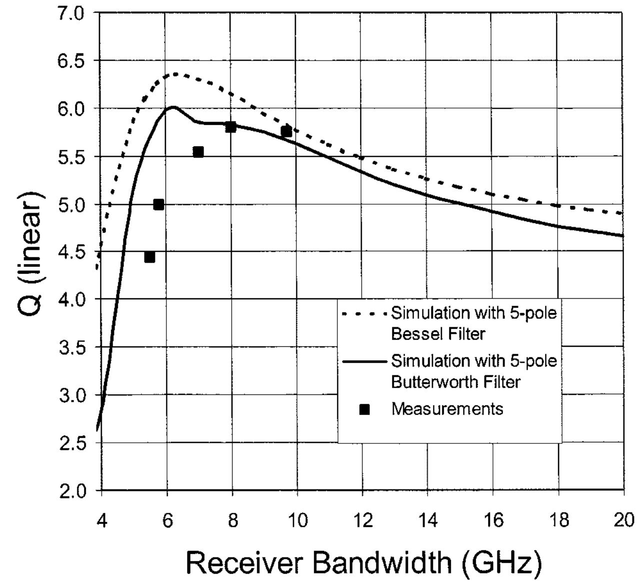

Fig. 4. Measured and simulated Q versus receiver bandwidth for the TB9 optical filter.

III. RESULTS

Figs. 4 and 5 show the measured and simulated Q versus receiver bandwidth for the TB9 and UDWDM FBG optical filters, respectively. The simulations are performed using the OptSim software package [9]. The optical bandpass filters are modeled in the simulations using the measured transfer functions for the TB9 and UDWDM FBG optical filters. Both Bessel and Butterworth five-pole filters are used to model the receiver electrooptic response. The measured Q is obtained from measurements of BER versus LA threshold voltage [10]. Thus, the measured data shows the BER equivalent Q.

The measurements show an optimum electrical bandwidth of 8 GHz for the receiver employing a TB9 optical filter, while the optimum electrical bandwidth is at least 1.7 GHz higher when

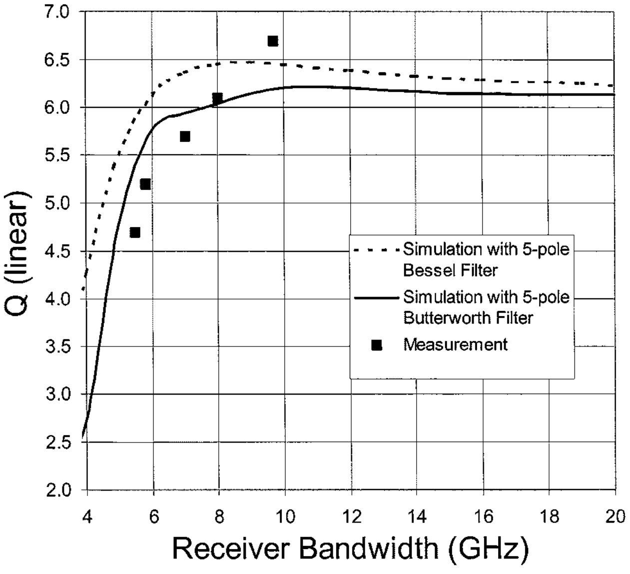

Fig. 5. Measured and simulated Q versus receiver bandwidth for the UDWDM FBG optical filter.

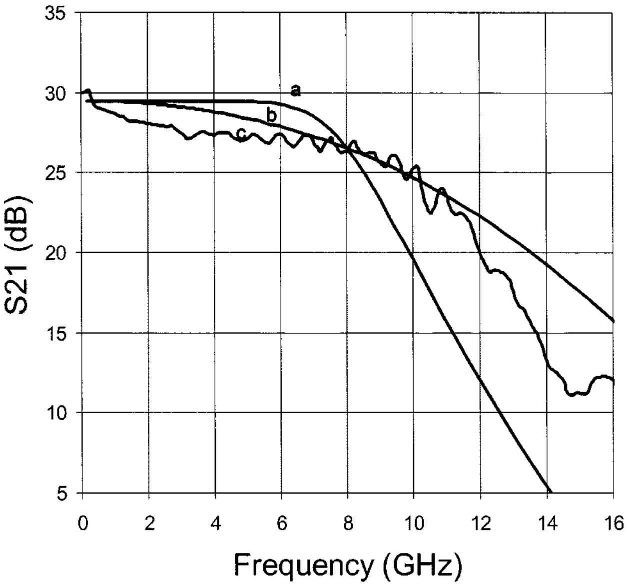

Fig. 6. Bessel and Butterworth filter models in comparison to measured S21 data. (a) Five-pole Butterworth filter. (b) Five-pole Bessel filter. (c) Measured S21.

using UDWDM FBG optical filter. Simulations confirm the trend to higher optimum receiver bandwidths for the UDWDM FBG optical filter. The best agreement between theory and experiment is obtained with the Butterworth filter, which gives a better fit to the sharp frequency rolloff in the receiver electrooptic response. The measured receiver electrooptic response also shows considerable ripple, which may limit the effective bandwidth to a lower value compared with our estimates. Thus, the measured optimum receiver bandwidths are higher than simulated. Fig. 6 shows a comparison between Bessel and Butterworth filter models for the receiver electrooptic response.

The measured data in Fig. 5 shows a 1.4-dBQ performance improvement when electrical receiver bandwidth is increased from 7 to 10 GHz for the UDWDM FBG filter. Moreover, comparing the measured Q for UDWDM FBG and TB9 in Figs. 4 and 5, respectively, the UDWDM FBG shows a 1.3-dBQ advantage. This illustrates the performance enhancement that may be gained in UDWDM systems by employing an optically matched demultiplexing filter with optimally designed receiver.

Interestingly, the simulation results imply that it should be possible to obtain almost the same performance with a wide bandwidth optical filter and optimum narrow bandwidth receiver as with a nearly matched narrow optical filter and wide bandwidth receiver. However, the ripple and sharp rolloff in the receiver electrooptic response prevented the receiver from reaching the optimum performance in the experiment as predicted by simulations for the TB9 optical filter. The simulations also ignore the deleterious effects of receiver group delay ripple. The UDWDM FBG optical filter shows a smooth amplitude response. Thus, it is easier to attain the optimum receiver performance experimentally by implementing a matched filter in the optical domain.

IV. CONCLUSION

An experimental and simulation study of optimum 10-Gb/s NRZ receiver bandwidths in the UDWDM limit was presented. Both theory and experiment confirm the scaling to higher optimum receiver bandwidths as channel spacing is reduced from 50 to 25 GHz. An optical FBG filter and electrical receiver matched for 10-Gb/s NRZ signals were demonstrated.

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