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基于 LabVIEW 的高分辨率光谱测试系统

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摘 要:提出了一种基于 LabVIEW 的无源器件光谱测试方案.通过 LabVIEW 编程控制可调谐激光器、可编程光滤波器、光功率计和数据采集平台,获得了具有不同传递函数的光谱特性.实验中激光器的扫描速度为 10 nm/s,扫描范围为 10 nm,数据采集卡的采样速率为 1 MS/s,结果表明:单个器件的光谱测试可以在 1 s 内完成,光谱分辨率可达 1 pm;与利用宽带光源和光谱分析仪的传统光谱测试方法相比,所提方案的测试性能可达到传统方案水平,且能显示更精细的光谱细节.该方案能应用于有高分辨率、快速和高效要求的光谱测试中.

关键词:光谱测试;光无源器件;可调谐激光器;LabVIEW;数据采集
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High Resolution Optical Spectrum Testing System Based on LabVIEW

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Abstract: A spectrum testing scheme of optical passive device based on LabVIEW was proposed. Relying on LabVIEW programming control over tunable laser, programmable optical filter, optical power meter and data acquisition (DAQ) platform, spectrum characteristics of various transfer functions could be obtained. When laser sweeping speed was 10 nm/s, sweeping range was 10 nm, and DAQ sampling rate was 1 MS/s, spectrum measurement for one device could be finished in 1 s, with spectrum resolution of 1 pm. Compared with conventional spectrum testing method utilizing broadband light source and Optical Spectrum Analyzer (OSA), the performance test scheme could achieve the traditional scheme level, and got more delicate spectrum details. The experimental results show that the proposed scheme can be applied for spectrum measurement with the demand of high resolution, fast speed and high efficiency.

Key words: Spectrum testing; Optical passive device; Tunable laser; LabVIEW; Data acquisition
OCIS Codes: 300.6190, 120.6200, 060.4510

0 Introduction

Optical spectrum analysis is one of the most fundamental tools in optical communication systems. Optical Spectrum Analyzers (OSA) are widely deployed in the diagnostic of transmitted optical signals, in the characterization of transfer functions of various kinds of active and passive optical devices, and in the monitoring of optical communication networks[1, 6-7]. In recent years, with the dramatic

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improvement of transmission rates and development of novel modulation formats, high resolution optical spectrum analysis is becoming increasingly necessary[2]. Currently, one way to acquire high resolution spectrum is relying on optical heterodyne technique, where the signal under test interferences with a local oscillator, subsequently radio frequency domain spectral analysis is performed[3-4]. Another promising method is based on Stimulated Brillouin Scattering (SBS) between a swept tunable laser and the signal under test[2, 5], which is also adopted in this paper.

Since the acquired optical spectrum information needs to be further processed in the electrical domain, high performance, real-time hardware circuit is also an essential element of the integral high resolution optical spectrum analyzer[6-10]. We utilized the Data Acquisition Card (DAQ) of National Instrument (NI) to acquire the mass data information account for the following reasons. On one hand, DAQs are high speed circuits which satisfy the need of real-time processing. On another, LabVIEW is a powerful software development environment that can easily control the hardware and interfaces, process the acquired data flow with predefined algorithms, and provide end users with easy-to-use Graphical User Interface (GUI).

This article is mainly focusing on the electrical-domain hardware and algorithm realization of the proposed high resolution optical spectrum analyzer.

1 Measurement principles and experimental setup

1.1 Measurement principles

The Signal Under Test (SUT) is injected to the High Non-Linear Fiber (HNLF), while the pumping wave, namely, the tunable laser signal, is propagating along the fiber in the opposite direction. The optical fiber is utilized as the medium to generate the Brillouin scattering after the interaction of the pump and SUT. The pump provides extremely narrow spectral window to pick up and amplify the corresponding spectral component of SUT. While the pump is tuning in a certain spectral range, the spectrum of SUT can be retrieved from the non-linear component of the Brillouin scattering effect[2, 5].

Such a process can be simplified as a tunable laser passing through a certain optical passive device with the spectrum feature we are interested in (equivalently SUT), which can be mathematically regarded as a convolution between the tunable laser and the filter profile of the optical passive device[11-12]. And the convolution output is just the counterpart of the non-linear component in the Brillouin scattering based on optical spectrum analyzing method, which can be illustrated in Fig. 1.

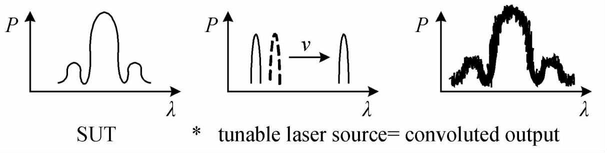


Fig. 1 Simplified process of Brillouin scattering

Hence, this paper investigates the property of the above simplified process. A more detailed and integral structure considering photo-electrical conversion and further signal processing is depicted in Fig. 2, where the whole process can be separated into optical and electrical domain.

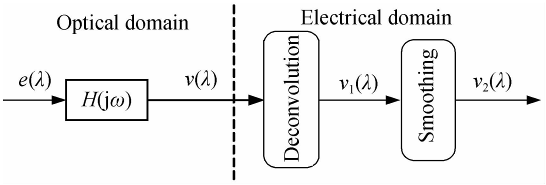


Fig2 Detailed structure of the simplified process

In Fig. 2, $e(\lambda)$ is the emitting power of tunable laser, $H(\mathrm{j}\omega)$ is the overall transfer function of filter with certain spectrum features, photo detector and current-voltage converting circuit. Here we represent the transfer function of optical filter, photo detector and current-voltage converting circuit by $H_\mathrm{f}(\mathrm{j}\omega)$, $H_\mathrm{d}(\mathrm{j}\omega)$ and $H_\mathrm{c}(\mathrm{j}\omega)$, respectively. Unit impulse responses of $H(\mathrm{j}\omega)$ and $H_\mathrm{f}(\mathrm{j}\omega)$ can be represented as $h(\lambda)$ and $r(\lambda)$, respectively. $v(\lambda)$ is the output signal passed through optical filter, photo detector and the converting circuit, which has the form of $V(\mathrm{j}\omega)$ in frequency domain. Obviously,

$$H(\mathrm{j}\omega)=H_\mathrm{f}(\mathrm{j}\omega)\cdot H_\mathrm{d}(\mathrm{j}\omega)\cdot H_\mathrm{c}(\mathrm{j}\omega)=RZ\cdot H_\mathrm{f}(\mathrm{j}\omega) \tag{1}$$

where R and Z are constants, the former one means the responsivity of detector, and the latter one means the resistance value of converting current into voltage.

Since in temporal domain (the wavelength value of tunable laser is proportional to time), we have

$$v(\lambda)=e(\lambda)*h(\lambda) \tag{2}$$

where $*$ represents convolution.

After converting Eq. (2) into frequency domain, and considering Eq. (1), we can obtain Eq. (3) as following.

$$V(\mathrm{j}\omega)=E(\mathrm{j}\omega)\cdot H(\mathrm{j}\omega)=\mathscr{F}(e(\lambda))\cdot H(\mathrm{j}\omega)=RZ\cdot\mathscr{F}(e(\lambda))\cdot H_f(\mathrm{j}\omega) \tag{3}$$

where $\mathscr{F}$ represents Fourier Transform.

Ideally, laser linewidth is considered to be 0 Hz, therefore

$$e(\lambda)=\delta(\lambda) \tag{4}$$

where δ represents the delta function.

Then Eq. (3) can be modified as

$$V(j\omega)=RZ\cdot H_p(j\omega) \tag{5}$$

From Eq. (5), we know that under the condition of omitting the effect of laser linewidth, $V(j\omega)$ is proportional to $H_p(j\omega)$. Therefore output voltage generated after passing through optical filter, photo detector and converting circuit can describe the spectrum characteristics of optical filters.

As a consequence, in this practical testing system, if the laser linewidth $\omega\Delta$ is narrow enough compared with the bandwidth of the filter, which is shown in Eq. (6),

$$\Delta\omega \ll \mathrm{BW} \tag{6}$$

where BW means the bandwidth of optical filter, where Eq. (5) realizes. If the above assumption does not hold true, the output spectrum would be broadened severely[6].

Besides, the most significant source of internal noise in the optical analyzing system attributes to the photo detector[13]. The convolution output inevitably suffers from noise disturbance, which leads to the unpleasant fluctuation along spectral axis. The above two factors contribute to the distortion of output spectrum, which is qualitatively shown in Fig. 1.

Hence, in order to eliminate the effect of convolution and stochastic noise, the acquired optical spectrum needs to be further processed in the electrical domain. In the rightmost part of Fig. 2, the retrieved optical spectrum is processed with deconvolution and smoothing algorithms to inhibit the side effect of convolution and random noise, respectively.

Deconvolution is the inverse process of convolution, which aims at restore the broadened spectrum of the optical filter. In Eq. (3), if the inverse transfer function of $\mathscr{F}(e(\lambda))$ is obtained, then we can get the Fourier transform of $v_1(\lambda)$ as

$$V_1(j\omega)=V(j\omega)\cdot\mathscr{F}^{-1}(e(\lambda))=RZ\cdot\widetilde{H}_f(j\omega) \tag{7}$$

where $\widetilde{H}_f(j\omega)$ is the approximation of the spectral feature of the optical filter, however the data flow after deconvolution still suffers from noise disturbance.

Subsequently, $v_1(\lambda)$ has to be divided into small portions where averaging is performed among elements in each portion, then the output spectrum $v_2(\lambda)$ is much smoother compared with $v_1(\lambda)$. Such an operation is essential because it eliminates the uncertainty brought in by random noise, which improves the fidelity of approximating the real spectrum.

1.2 Experimental setup

The layout of high resolution optical spectrum measuring system proposed in this article is shown in Fig. 3.

The tunable laser type is Santec TSL-510, with maximum output power up to 2 dBm, laser linewidth of about 500 kHz measured by Agilent E4447A spectrum analyzer . In order to verify the testing performance of the proposed method for different optical spectrum features, we choose a programmable optical filter, Finisar WaveShaper 4000S, to simulate spectrum characteristics of certain optical passive devices, which can be realized by predesigning optical transfer functions of WaveShaper S4000. The photo-electrical converting section is realized by a Newport 1936-C power meter, equipped with an 818-IS-1detector, it can detect low level optical power precisely. Data acquisition system is the platform provided by National Instruments, a windows embedded PXIe-8133 controller and a PXIe-5122 data acquisition card with sampling rate up to 200 MS/s are inserted into the PXIe-1082 metal classis, which can be seemed as a special purpose computer.

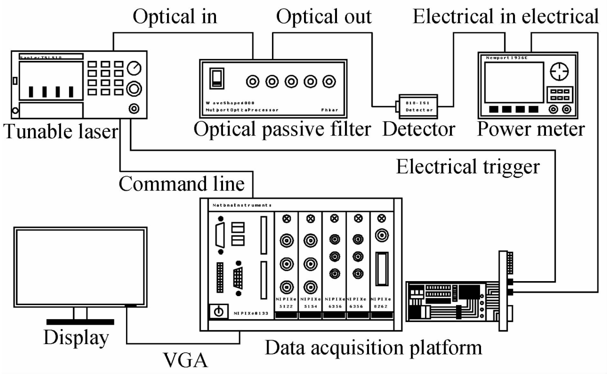


Fig. 3 Layout of spectrum measurement system

The platform is equipped with GPIB, RS-232 and USB interfaces, LabVIEW programs run on Windows XP operation system installed on PXI-8133, which coordinate working conditions between internal data acquisition card and external devices precisely via communication interfaces. Meanwhile, analog electrical signal will be converted to digital domain. Algorithms such as smoothing and deconvolution are performed in this unit. In this whole system, the tunable laser, optical passive devices, optical power meter and data acquisition platform are interconnected via optical or electrical cables.

To be more specific, regarding Fig. 3, the working state of tunable laser TSL-510 is set by receiving command from PXIe-8133 controller through a GPIB interface. Wavelength sweeping range is from a certain starting wavelength to an ending wavelength, with maximum sweeping range of 50 nm starting from 1 510 nm to 1 630 nm, which covers the whole C and L band. TSL-510 can sweep in continuous mode and step mode. Here in our experiment, in order to achieve high speed testing performance, we require the laser to work in continuous sweeping mode. In such a mode, sweeping speed can also be set, with maximum sweeping speed up to 100 nm/s. Take the issue of synchronization with DAQ platform into consideration, we set laser sweeping speed as 10 nm/s. Once TSL-510 starts to sweep, a pulse-shaped trigger signal is generated immediately from the BNC interface on the rear panel of tunable laser, with maximum voltage of 3.11 V. The trigger signal is used as a messenger to activate the behavior of data acquisition of PXIe-5122. The optical signal generated by TSL-510 is then sent to WaveShaper 4000S. After passing through a certain optical transfer function, the output signal is received by detector 818-IS-1 attached by power meter 1936-C, during which optical power is converted into current through detector, and current is converted into voltage through power meter. The analog voltage output can be retrieved from BNC interface on the rear panel of 1936-C. Once received trigger impulse from tunable laser, PXIe-5122 starts to acquire data continuously with sampling rate of 1 MS/s, after that the obtained data are processed and displayed.

Considering the software programming located in the DAQ platform, LabVIEW is used to control the wavelength sweeping mode of tunable laser, the working condition of data acquisition card and the processing of obtained data flow. Fig. 4 is the block diagram illustrating the software functionality.

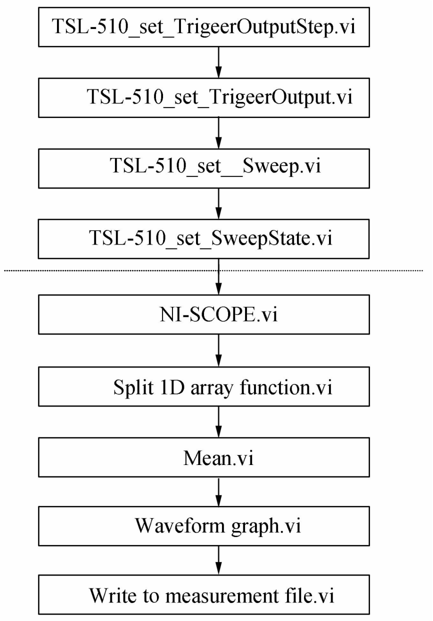


Fig. 4 Block diagram of LabVIEW program

The upper part in Fig. 4 is the implementation of laser control via GPIB interface. According to the user′s command, working parameters of the tunable laser can be set as what the trigger mode is, how the sweeping condition is, and when the sweep starts. Specifically, Users can modify sweeping parameters such as starting wavelength, ending wavelength, sweeping speed and the timing of trigger generation. And then such parameters are read by VIs such as TSL-510_set_Sweep.vi, TSL-510_set_SweepState.vi, etc. in block diagram, altogether acting as hardware drivers of TSL-510. Here we set the sweeping range from 1 540 nm to 1 550 nm, and sweeping speed is set to be 10 nm/s.

The lower part of this chart illustrates how the acquired data are processed through .vi modules. After the reception of trigger signal from the tunable laser, data acquisition card immediately obtain 1 000 000 points of data with sampling rate of 1 MS/s, and then the obtained data flow is processed and displayed.

Note that the frequency separation between any two adjacent sample points is 0.01 pm, and the laser linewidth of tunable laser is around 500 kHz, namely 4 fm in the dimension of wavelength, considerably narrow compared with the bandwidth of our testing filter spectrum of up to several nanometers, which means the linewidth has almost no effect on any two sample points. Hence, deconvolution is not a prerequisite for further processing. Besides, the deconvolution algorithm is time-consuming, which hampers the real-time display of tested spectrum. So we can make a modification of signal processing in Fig. 2 by deleting the section of deconvolution. And the subsequent smoothing algorithm can still work well.

So here we utilize NI-SCOPE Express.vi to obtain 1 000 000 points of data by converting analog signals into discrete ones; Then the massive discrete points are divided into 10 000 proportions with length of 10 points by Split 1D Array Function.vi, which means the 10 nm range is divided into 10,000 segments corresponding to 10 000 values of wavelength, hence the spectrum resolution of 0.001 nm can be achieved; In every segment, the first 5 points are used for averaging, which is realized by Mean.vi. After times of testing, we find the phenomenon that if more points are taken to perform averaging, the details of the optical spectrum will be smoothed out; if fewer points are chosen, the random fluctuation cannot be effectively cancelled. And the mean value is chosen as the received signal power of the current wavelength; After that, Waveform Graph.vi is applied to display the processed output data flow; Finally, Write to Measurement File.vi to store the processed data into .txt or .lvm format for analysis. At last, we discuss the factors affect the minimum resolution of our proposed system.

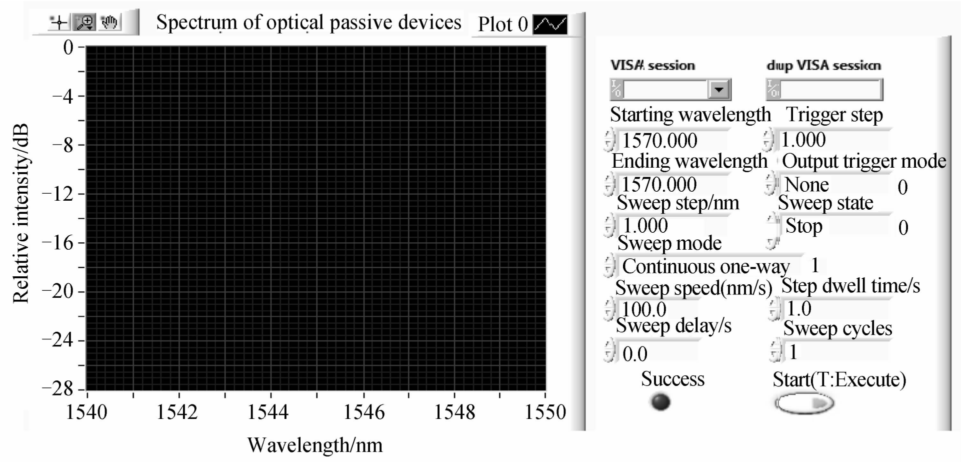
According to the commercial used spectrum testing products based on scanning scheme such as Aragon and Agilent, 10 nm/s is the commonly used scanning speed[3,5]. That is because a much higher speed leads to the fluctuation of optical power, which negatively affects the testing accuracy. Besides, in a real-time testing environment, the scanning time should not exceed 1 s. So if the sweeping range is 10 nm, then our prototype should finish scanning and further processing in about 1 s.

Also, since the detector bandwidth restricts the allowed spectrum component to pass. In our system, the detector bandwidth is 400 kHz. According to the Nyquist theory, sampling rate of 1 MS/s is adequate to retrieve all the information of the received signal, unless a higher bandwidth can be achieved. But an even higher sampling rate will not result in representing more details. Hence, 1 MS/s is the optimal sampling rate, which further means that 1 000 000 points are recorded. Considering the averaging propose discussed above, the 1 000 000 points are divided into 10 000 groups, corresponding to 10 000 wavelengths.

That is, in a scanning range of 10 nm, our best testing resolution is 1 pm, which is restricted by the detector bandwidth.

2 Spectrum measuring experimental results

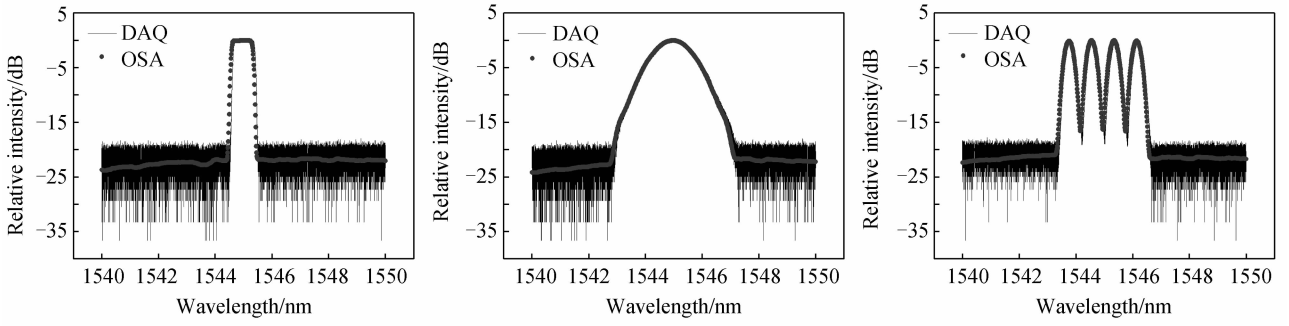
The front panel provides user with an intuitive and operable Graphical User Interface (GUI), which is illustrated in Fig. 5.



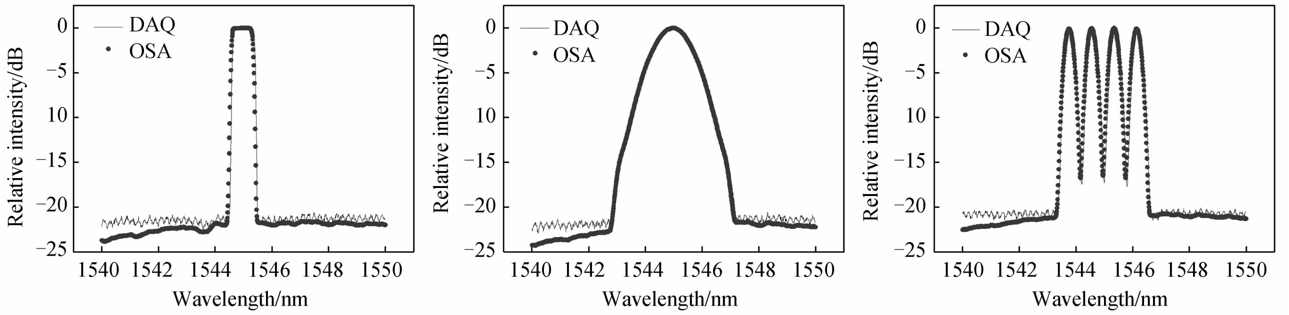
VISA session
dup VISA session
Starting wavelength 1570.000
Trigger step 1.000
Ending wavelength 1570.000
Output trigger mode None 0
Sweep step/nm 1.000
Sweep state Stop 0
Sweep mode Continuous one-way 1
Sweep speed(nm/s) 100.0
Step dwell time/s 1.0
Sweep delay/s 0.0
Sweep cycles 1
Success
Start(T:Execute)

Fig. 5 Front panel of the optical spectrum testing system

In order to verify the spectrum measuring performance of various types of optical filters, we design rectangular, Gaussian and periodically sine-shaped filters with the assistance of WaveShaper 4000S. In Fig. 6, we set isolation=22 dB for different optical passive devices. Without performing smoothing algorithm, spectral characteristics obtained by data acquisition system of different optical passive components are shown as black curves (DAQ) from Fig. 6(a) to Fig. 6(c).



(a) Rectangular spectrum before smoothing (b) Guassian spectrum before smoothing (c) Sinusoidal spectrum before smoothing



(d) Rectangular spectrum after smoothing (e) Guassian spectrum after smoothing (f) Sinusoidal spectrum after smoothing

Fig. 6 Spectrum measuring performance before and after smoothing

Meanwhile, for intuitive contrast between our proposed spectrum measuring method and conventional one, we utilize LIGHTCOMM C-band ASE light source to pass through WaveShaper 4000S when simulating different optical passive devices, and then send the output signal to traditional diffraction grating based optical spectrum analyzer Agilent 86140B, the recorded spectrum characteristics are shown as dotted line (OSA) from Fig. 6 (a) to Fig. 6(c), respectively, from which we can see that, spectrum patterns obtained by DAQ method and OSA method match reluctantly. That is because smoothing algorithm has not been performed, which leads to the situation that spectral components with low power level are affected by noise strikingly.

After performing smoothing algorithm, spectrum testing performance of DAQ and OSA methods can be shown in Fig. 6(d) to Fig. 6(f). Considering the rectangular situation, our scheme has a satisfied performance facing spectrum mutations. And from the comparison between Gaussian and periodically sinusoidal situations, we can make the conclusion that our method is able to identify detailed information of spectral features.

We believe that the proposed LabVIEW based testing scheme has the performance approaching to the conventional one relying on broadband light source and diffraction grating based optical spectrum analyzer with even higher resolution. Although there are fluctuations around bottom part of the DAQ obtained spectrums, the overall trends of black curves can represent real spectrum characteristics under such experiment conditions. The bottom fluctuation attributes to the restriction from detecting lower optical power. Such phenomenon is caused by detector and data acquisition card introduced noise. Since the accuracy of PXIe-5122 is 14 bits for A/D conversion, weak signals cannot be distinguished from such thermal noise. As a result, our scheme has a limitation on detecting a certain low power level signal, so the fluctuation of bottom part of optical spectrum by DAQ method is the representation of inaccurate detection of optical power.

Hence, conclusions can be made that our proposed LabVIEW based testing scheme has the performance approaching to the conventional one relied on broadband light source and optical spectrum analyzer. Besides, due to fast sweeping speed of tunable laser and data processing ability of DAQ platform, time duration of single sweep can be reduced dramatically compared with that using conventional method. As a consequence, the efficiency of spectrum testing is enhanced.

3 Conclusion

In this paper, we proposed and realized an optical spectrum testing system based on software LabVIEW. The whole system consists of the tunable laser, detector, power meter, data acquisition platform, and display unit.

By setting laser sweeping speed as 10 nm/s, sweeping range as 10 nm, and DAQ sampling rate as 1 MS/s, spectrum measurement for one device can be finished in 1 s, with our best spectrum resolution of 1 ps, which is restricted by the detector bandwidth. Our prototype has achieved high resolution and approaches the performance of conventional spectrum measuring method utilizing broadband light source and optical spectrum analyzer. Thus, the LabVIEW based spectrum testing method is suitable for spectrum characteristic discretion of optical passive devices.

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