Widely Tunable Twin-Beam Light Source based on Quasi-Phase-Matched Optical Parametric Generator as a Spectral Responsivity Comparator between InGaAs and Si Photodiodes

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Abstract. We present a twin-beam light source based on quasi-phase-matched (QPM) continuous-wave (CW) optical parametric generator (OPG). The source emits collinearly the signal and the idler beams at a power level of 1 nW in wavelength ranges from 790 nm to 920 nm and from 1260 nm to 1620 nm, respectively, with a bandwidth of less than 2 nm. The quantum correlation in the OPG process can be used to directly compare the spectral responsivity of an InGaAs photodiode with that of a Si photodiode, offering a new calibration method for InGaAs photodiodes.

1. Introduction

A twin-beam light source simultaneously emits two beams that are strongly correlated but distinguishable. Most such sources are based on parametric wavelength conversion in an optically nonlinear medium, which convert the incident pump laser beam into two lower-energy beams called the signal and the idler. Of particular interest for photometry and radiometry is the device based on spontaneous parametric down-conversion (SPDC) with its potential application for absolute calibration of detector quantum efficiency by single-photon coincidence counting [1-3]. With SPDC, however, only photon-counting detectors such as photomultipliers or avalanche photodiodes can be calibrated at a low power level, and the wavelength tunability is limited.

At power levels above several microwatts, a CW optical parametric oscillator (OPO) is a useful coherent twin-beam source. Tunability in a wide wavelength range can be achieved by applying the quasi-phase-matching (QPM) technique [4]. The quantum correlation between the signal and idler beams from an OPO is influenced by the cavity and can be characterized, e.g., by measuring the noise spectrum of the photocurrent difference [5]. Twin-beam based radiometric metrology using tunable OPOs is one of our on-going research topics at KRISS.

In this paper, we report on an optical parametric generator (OPG) as a wavelength-tunable twin-beam light source, which offers an interesting application for IR photodiode calibration. An OPG consisting of a pump laser and a nonlinear crystal is in essence a building block for an OPO that has an optical cavity added to an OPG. We distinguish, however, an OPG from SPDC in the aspect that the optical modes of the OPG output beams are defined by the pump laser mode propagating collinearly in a long crystal (usually longer than 1 cm). The spectral power density of OPG is therefore much larger than that of SPDC. We have developed an OPG emitting the signal beam in a wavelength range detectable with a Si photodiode, and the idler beam detectable with an InGaAs photodiode. Based on the quantum correlation between the numbers of generated signal and idler photons, the spectral responsivity of two detectors at different wavelengths can be directly compared by measuring the photocurrent ratio. We present first the experimental setup and characteristics of the OPG twin-beam source, and then introduce the principle of spectral responsivity comparison. Finally, the major systematic error source of IR photodiode calibration using the OPG is stated.

2. The OPG Twin-Beam Source

Figure 1 shows the schematic setup of the OPG source. As the pump laser, we use a frequency-doubled CW Nd:YAG laser providing a 1-W single-mode beam at 532 nm. After passing through a concave lens (f = 150 mm), a Faraday isolator, and a half-wave plate (HWP), the pump beam is collimated to a diameter of approximately 1 mm, which is then focused using a lens (f = 100 mm) to the center of the nonlinear crystal.

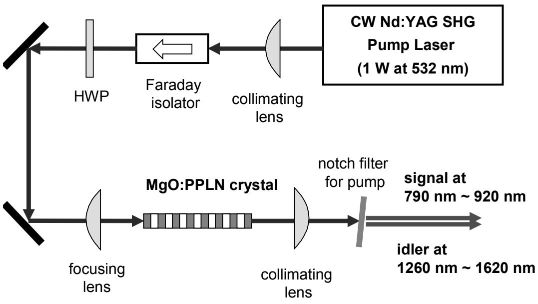

Figure 1. Schematic setup of the tunable twin-beam source based on quasi-phase-matched CW OPG.

For the nonlinear crystal, we use a MgO-doped periodically poled lithium niobate (MgO:PPLN) that is 40 mm long, 13 mm wide, and 0.5 mm thick. The crystal has six poling periods of from 7.1 μm to 7.6 μm for QPM, and is mounted in a temperature-controlled oven with stability better than ± 0.05 ˚C. The generated signal and idler beams from the crystal are collimated using a lens (f = 100 mm), and the pump beam at 532 nm is blocked out with a holographic notch filter. The collinearly propagating signal and idler beams can be separated using a dichroic beam-splitter.

The wavelength and spectral shape of the signal and the idler beams are measured with a double-grating optical spectrum analyzer (Agilent 8614B). Figure 2 shows the measured peak wavelength as a function of poling period (Λ) and crystal temperature. The signal and the idler wavelengths can be tuned from 790 nm to 920 nm and from 1260 nm to 1620 nm, respectively. The spectral bandwidth remains within 1 nm and 2 nm (FWHM) over the whole tuning range. The radiation power of the OPG output beams is on the order of 1 nW, which is sufficient for photocurrent detection with conventional photodiodes and low-noise pre-amplifiers.

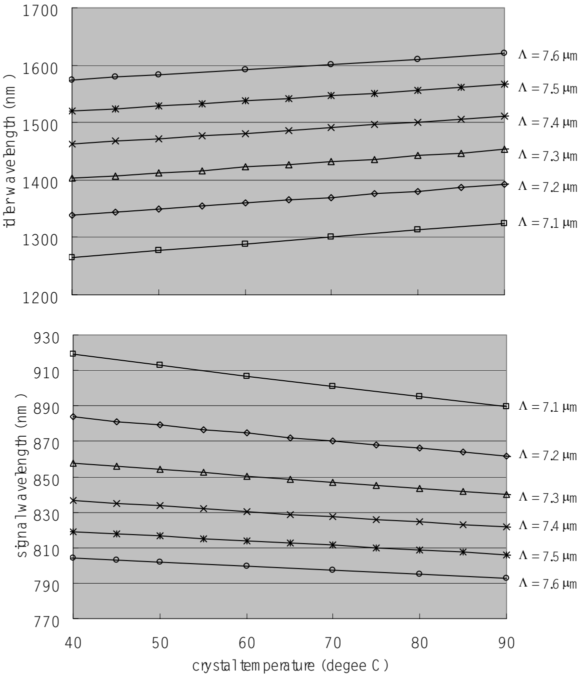

Figure 2. Measured signal and idler wavelengths of the QPM OPG as a function of poling period and crystal temperature.

3. Spectral Responsivity Comparison

The optical parametric conversion process creates one signal photon and one idler photon in pair by annihilating one high-energy pump photon, so that the flux rate N (in number of photons per second) of the signal and idler photons from the OPG is the same:

$$N_S = N_I \tag{1}$$

This quantum correlation is at the heart of the absolute calibration method of photon counting detector efficiency using SPDC [1-3]. Our approach using OPG is for relative calibration of detector quantum efficiency, but the method can be applied generally to photodiodes producing photocurrents proportional to the incident radiation power.

In our OPG twin-beam source, the signal beam can be optimally detected with a Si photodiode (designated with index 1), while the idler beam with an InGaAs photodiode (designated with index 2). The ratio of the measured photocurrents I_1/I_2 is then given as

$$\frac{I_1}{I_2} = \frac{R_1 P_S}{R_2 P_I} \tag{2}$$

with the power responsivities R_1 and R_2 of the Si photodiode and the InGaAs photodiode, respectively, and the signal and idler powers P_S and P_I, respectively, incident on the detector active area. Note that the photocurrent ratio in Eq. (2) is the same as the ratio of the quantum efficiencies of the two photodiodes at the given wavelengths. Using Eq. (1), the power ratio P_S/P_I in Eq. (2) can be written as

$$\frac{P_S}{P_I} = \frac{N_S}{\lambda_S} \cdot \frac{\lambda_I}{N_I} \cdot \frac{T_S}{T_I} = \frac{\lambda_I T_S}{\lambda_S T_I}. \tag{3}$$

Here, T_S and T_I are the transmissions from the OPG crystal to the detector at the signal and the idler wavelengths λ_S and λ_I, respectively. The ratio of the spectral power responsivities finally follows from Eqs (2) and (3):

$$\frac{R_2}{R_1} = \frac{I_2 \lambda_I T_S}{I_1 \lambda_S T_I}. \tag{4}$$

From Eq. (4) we see that, using the OPG twin-beam source, two photodiodes of different types, i.e., a Si and an InGaAs photodiode, can be directly compared in their spectral power responsivity by measuring the photocurrent ratio at different signal and idler wavelengths. The transmission ratio is a property of the experimental setup, which needs to be characterized once.

As the spectral responsivity standard usually is disseminated by Si photodiodes, Eq. (4) can be used to calibrate InGaAs photodiodes, which are the most widely used IR detectors, with respect to the Si-based responsivity standard. The potential advantage of this new calibration method for InGaAs photodiodes is the absence of a thermal detector as a transfer standard between different wavelengths, thereby overcoming the present limits on sensitivity and accuracy of IR detector calibration. However, the new method requires still more study on possible systematic errors and uncertainty factors, which are presently under investigation.

Preliminary experimental results show that a discrimination of the OPG modes from those of spontaneous parametric fluorescence is of particular importance for accurate calibration. Because the crystal has a considerable length of 40 mm, the spontaneous parametric fluorescence from each length element of the crystal can be collected in the detector accumulating a comparable amount with that of the OPG modes. We experimentally found out that the detection of spontaneous fluorescence significantly violates the correlation of Eq. (1) due to the large difference between the signal and idler wavelength values. Discrimination of the OPG modes is successfully achieved by using a pinhole-based spatial filter, resulting in a correct calibration of InGaAs photodiode responsivity compared with that of the conventional method using a thermal detector. We will present the results of our investigation regarding this effect and other factors affecting the accuracy of the proposed calibration method.

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