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Miniaturisiertes Quantenlichtmodul zur Mikroplastikdetektion: MIR-Spektroskopie mittels verschränkter Photonen

Miniaturized Quantum Light Module for Microplastic Detection: MIR Spectroscopy Using Entangled Photons

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Kurzfassung

Spektroskopie im mittleren Infrarotbereich (MIR) ist aufgrund der hohen Eindringtiefe der MIR-Strahlung ein leistungsfähiges Werkzeug zur Analyse stark streuender Materialien wie (Mikro-)Plastik. Herkömmliche MIR-Quellen und -Detektoren sind jedoch in der Regel groß, teuer und technisch sehr anspruchsvoll. Daher wurde ein quanteninterferometrischer Aufbau basierend auf spontaner parametrischer Fluoreszenz (SPDC) in einem nichtlinearen ppKTP-Kristall zur Erzeugung verschränkter NIR-MIR-Photonenpaare realisiert. Nach der Erzeugung interagiert das MIR-Photon mit der Polymerprobe, während das verschränkte NIR-Photon einen Referenzweg durchläuft und von einem herkömmlichen Spektrometer detektiert wird. Aufgrund der Quantenverschränkung können Informationen über die Wechselwirkung des MIR-Photons mit der Probe allein durch die Detektion des NIR-Photons abgeleitet werden. Diese als „sensing with undetected photons” bezeichnete Technik ermöglicht MIR-Spektroskopie ohne direkte MIR-Detektion. Durch hochpräzise Mikrointegration und einen gefalteten Strahlengang für den Referenzarm konnte der optische Aufbau miniaturisiert und auf einer Fläche von nur 75 mm x 90 mm aufgebaut werden. In dieser Konfiguration wurden Photonenraten von über 10^9 pro Sekunde pro Watt Pumpleistung sowie eine Quanteninterferenz-Visibility von ≈ 30 % erzielt. Diese Ergebnisse unterstreichen die Eignung der entwickelten Module für mobile Anwendungen, wie etwa die vor-Ort Analyse von Mikroplastik in Abwasser, und stellen einen wichtigen Schritt in Richtung industrietauglicher Lösungen dar.

Abstract

Mid-infrared (MIR) spectroscopy is a powerful tool for analyzing highly scattering materials, such as (micro-)plastics, due to the high penetration depth of MIR radiation. However, traditional MIR sources and detectors tend to be large, expensive, and technically challenging. To overcome this limitation, a quantum interferometric setup based on spontaneous parametric down-conversion (SPDC) in a nonlinear ppKTP crystal was implemented to generate entangled NIR-MIR photon pairs. After generation, the MIR photon interacts with the polymer sample, while the entangled NIR counterpart travels through a reference path and is detected by a conventional spectrometer. Due to the quantum entanglement, information about the MIR photon’s interaction with the sample can be inferred by detecting only the NIR photon. This technique, which is known as "sensing with undetected photons", enables MIR spectroscopy without the need for direct MIR detection. Using high-precision micro-integration and a folded beam path for the reference arm, the setup was miniaturized and built on an area measuring only 75 mm x 90 mm. In this configuration, photon rates exceeding 10^9 per second per watt of pump power and quantum interference visibility of ≈ 30 % were achieved. These results highlight the suitability of the developed micro modules for mobile and field-deployable applications, such as on-site microplastic analysis in wastewater, and marks a key step toward industry-ready solutions.

1 Introduction

Microplastics are ubiquitous and pose a growing threat to human health and the environment. However, detecting and identifying microplastic particles remains a major challenge due to their small size, the often low number of particles and the need for complex sample preparation. This process is further complicated by the high susceptibility of microplastics to contamination, such as from organic materials, and by the wide variety of existing polymer types, for which suitable reference materials are often lacking [1]. As a result, rapid and reliable on-site analysis, e.g. of wastewater samples, is both technically demanding and critically important, as it enables early detection and effective mitigation of potential health and safety risks. Mid-infrared (MIR) spectroscopy ($\lambda > 3\ \mu m$) has established itself as a powerful, non-destructive technique for the identification and characterization of polymer materials. However, conventional MIR sources and detectors are typically large, expensive, and technically complex, which significantly limits their applicability outside controlled laboratory environments [2]. This paper presents a novel approach to MIR spectroscopy based on the generation of entangled MIR-NIR (near-infrared) photon pairs within a quantum interferometric setup. With this method, the sample is irradiated with MIR light, but detection of the MIR radiation is not required. Instead, the NIR photons, that are quantum mechanically entangled with the MIR photons, are detected and provide information about the sample. This innovative approach opens up a wide range of potential applications, especially for the analysis of materials at wavelengths for which no suitable detection mechanism currently exists.

The Ferdinand-Braun-Institut has succeeded in significantly miniaturizing this complex optical setup on a footprint measuring only 75 x 90 mm. This marks a decisive step towards mobile and user-friendly analysis of microplastic samples, opening up new possibilities for applications beyond traditional laboratory settings.

2 Concept and Design

This section describes the concept and optical design of the quantum module and its integration into the overall system. Afterwards, the assembly strategy of the micro-module is briefly outlined.

2.1 Interferometric Module

The interferometric setup is shown on the left-hand side in Figure 1. First, pump radiation is coupled into the module, collimated and focused into the center of a 30 mm long nonlinear crystal. In the periodically poled potassium titanyl phosphate (ppKTP) crystal, an incident pump photon is converted into an entangled signal–idler photon pair through spontaneous parametric down-conversion (SPDC). The frequencies of the generated photons are related through energy conservation, written as $\omega_P = \omega_S + \omega_I$ [2].

The module is designed to generate MIR radiation in the wavelength range from 3.2 to 3.6 µm, as many polymers exhibit characteristic absorption spectra in this spectral range. This results in wavelengths for pump and idler as shown in the Table below.

Radiation	**Wavelength**
Pump beam	720 nm
Signal beam	900-930 nm (NIR)
Idler beam	3.2-3.6 µm (MIR)

The resulting spectra for signal and idler appear to be very broad due to group-velocity matching of signal and idler realized by collinear type-0 quasi-phase matching (QPM) [2]. In order to meet the QPM conditions and thus achieve the desired signal and idler wavelengths and bandwidths, the crystal properties, in particular poling period and temperature, must be precisely matched to the properties of the pump laser, such as wavelength and polarization. A large bandwidth of the generated photon pairs is crucial for spectroscopy applications as it enables the investigation of samples over a wider spectral range [2].

A dichroic mirror behind the crystal separates MIR from NIR and pump beam, whereupon the MIR radiation leaves the module and interacts with the desired plastic sample. Meanwhile, signal and pump beam are propagating along a reference path within the module. The two lenses form a *4f* imaging system beginning at the middle of the crystal up to the end mirror of the reference path, minimizing chromatic aberrations that occur due to the large spectral bandwidth of the SPDC radiation and the wavelength difference between pump and signal. All the light is ultimately reflected back into the center of the crystal.

Here, interference occurs between backward propagating signal photons generated during the first pass and signal photons generated during the return pass through the crystal. Another dichroic mirror directs the NIR radiation out of the module and into a spectrometer. Due to wavelength-dependent phase differences, intensity modulations appear in the spectrum of the signal radiation, resulting in characteristic interference fringes.

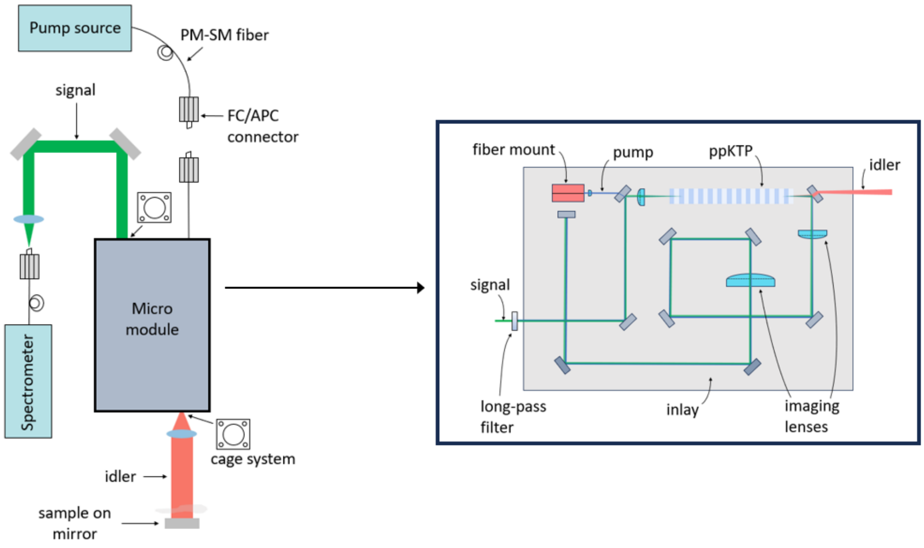

Figure 1 Optical layout of the micro module (*right*) and the overall experimental setup (*left*). Pump beam (*blue*) decays into signal (*green*) and idler (*red*) beam in the 30 mm long ppKTP crystal. The folded reference arm, starting at the second dichroic mirror behind the crystal, has a length of approx. 17 cm.

However, because the signal and idler photons are quantum-mechanically entangled, interference in the signal spectrum can only be observed if the idler path is precisely aligned and the two SPDC generation processes remain coherent and indistinguishable.

Consequently, if a sample that partially or completely absorbs MIR wavelengths is placed in the idler beam path, those altered spectral components are no longer indistinguishable and do not contribute to the quantum interference. In the NIR spectrum, this manifests as the disappearance of modulation in the corresponding spectral regions. The resulting changes in the signal spectrum can therefore be used to indirectly determine the absorption or transmission spectrum of the sample in the MIR range.

2.2 Overall Optical Setup

The integration of the module into the overall setup is shown on the right-hand side of Figure 1. The pump radiation is delivered via a polarization maintaining (PM) single mode (SM) fiber and an FC/APC fiber connector.

The MIR radiation propagates outside the module within a ~17 cm long standard 16 mm cage system, which contains a collimation lens. At the end of the cage system, an MIR-reflecting mirror is mounted, above which the polymer sample is positioned. Additionally, a focusing lens can be inserted to enable the investigation of smaller structures, such as microplastic particles. The NIR radiation also exits the module as a free-space beam and is coupled into the fiber leading to the spectrometer via two mirrors and a focusing lens mounted in another cage system. Moreover, another long-pass filter is positioned in the signal beam path to remove residual pump light. The high number of available degrees of freedom allows for continuous optimization of the coupling with respect to pump power, wavelength or idler alignment, enabling fine adjustment of the count rate in the spectrometer.

Another module was built with integrated FC/APC fiber connectors and internal fiber coupling of the signal radiation (Figure 2), enabling fast and efficient connection to both the pump source and the spectrometer. The adaption makes this module particularly user-friendly and allows for easy and compact integration into the overall setup.

2.3 Module Assembly

The module assembly was carried out using high-precision micro-integration technology and a combination of active and passive mounting techniques. In the active mounting approach, the optical components are positioned while the laser source is operating and subsequently fixed in place using UV-curable adhesive. In contrast, passive assembly relies on mechanical boundaries within the inlay that define the positioning of the optical components, without the use of an active laser source. While passive assembly enables highly time-efficient placement of the optical components, active assembly provides superior positioning accuracy. The fixation and alignment of the optical components are carried out using hexapods and vacuum tweezers, enabling highly precise positioning with step sizes as small as 100 nm.

Figure 2 Inside view of an SPDC module with integrated fiber connectors and internal fiber coupling of the signal radiation.

The inlay is fabricated from gold-plated copper-molybdenum, whereas the housing is made of anodized aluminum. The inlay has dimensions of 60 mm x 34 mm, and the overall module measures 75 mm x 90 mm. Furthermore, the module integrates a Peltier element for temperature control of the crystal, ensuring stable thermal conditions during operation.

3 Results

This section presents the basic functionality of the module, from quantum interference to plastic sample analysis.

3.1 Quantum Interference and Visibility

Figure 3 shows the measured NIR spectrum with and without quantum interference, e.g. with and without idler arm alignment, as well as the pure oscillation derived from the subtraction of the two spectra. The spectra were recorded at a pump wavelength of 720.8 nm, a crystal temperature of 40 °C, and an optical power of 15 mW within the module. The crystal used features a poling period of 23.375 µm. The spectrometer itself had an integration time of 50 ms and averaged over ten individual spectra. Overall, this results in a NIR photon count rate of > 10^9 per second per watt of pump power.

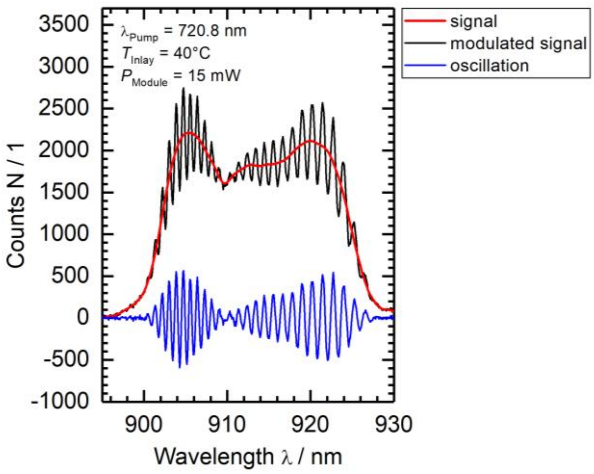

Figure 3 NIR spectrum with (*black*) and without (*red*) quantum interference fringes, as well as separated oscillation (*blue*).

The visibility of the interference fringes is defined as $\nu = N_{max} - N_{min}/N_{max} + N_{min}$, which corresponds to the oscillation amplitude divided by the mean intensity. As can be seen in Figure 3, the visibility decreases towards the edges of the spectrum and reaches a local minimum around 910 nm. The drop in visibility in the center of the spectrum is attributed to intrinsic absorption within the crystal. Consequently, while a longer crystal increases the SPDC yield and thus the photon count rate, it also enhances self-absorption effects, leading to a loss of visibility. Considering only the two spectral regions with pronounced oscillations, an average visibility of approximately 30 % is obtained.

The alignment of the idler arm is crucial for achieving high visibility, as even slight angular deviations or changes in the idler path length reduce the indistinguishability of the SPDC processes. Consequently, the visibility decreases symmetrically with increasing misalignment around the point of maximum visibility [3].

Furthermore, the visibility, photon count rate, and spectral bandwidth strongly depend on the crystal temperature (see Figure 4). As the temperature decreases, the NIR spectrum becomes broader, while the visibility is reduced. This behavior can be attributed to a deviation from the QPM condition. When selecting the crystal temperature, it is essential to balance the generation of a broad spectrum with sufficiently high visibility to ensure that a meaningful transmission spectrum can be derived.

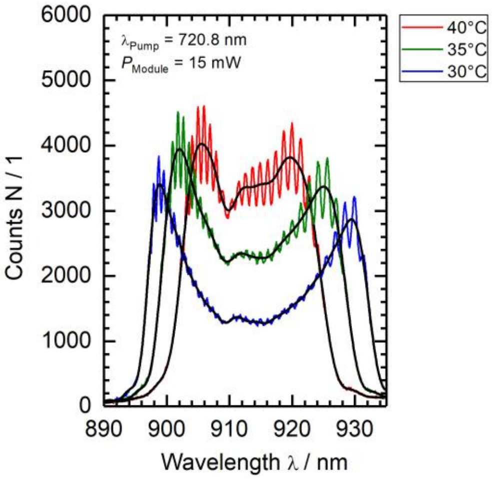

Figure 5 NIR spectrum for a crystal temperature of 30 °C (*blue*), 35 °C (*green*) and 40 °C (*red*).

3.2 Plastic Sample Identification

Figure 6 illustrates how the NIR spectrum with quantum interference changes when a sample is placed in the aligned MIR path. The modulation disappears entirely or partially in certain spectral regions. If both spectra, namely the modulated and the reference spectrum, are available, the envelopes of the interferograms can be obtained using a Hilbert transform, and from these the transmission curve of the sample in the MIR wavelength range can be determined. In this experiment, a plastic foil with a thickness of approximately 30 µm was mounted in the collimated beam path and analyzed. The spectrum shown was recorded with an integration time of 100 ms and an average of seven individual spectra.

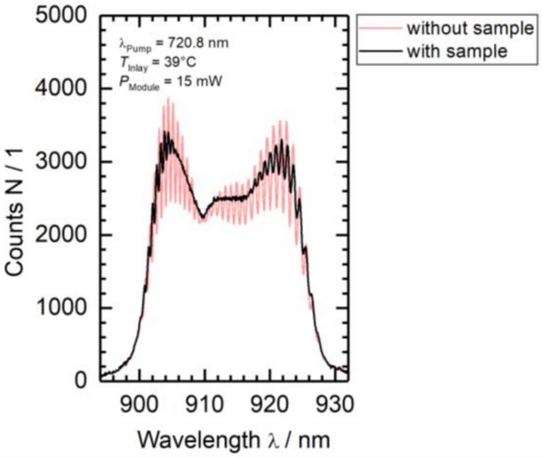

Figure 6 NIR spectrum with and without polymer sample placement in the idler arm.

4 Summary and Outlook

This paper presented the miniaturized implementation of a quantum interferometric setup for the generation of entangled NIR–MIR photon pairs. The compact design paves the way for transferring this technology from the laboratory to mobile systems, enabling applications such as wastewater analysis for microplastic detection. The basic operating principle of the module was demonstrated by examining a thin plastic foil placed in the aligned idler beam path.

Current efforts focus on the design of MIR-compatible microfluidic units, where microplastic particles can be aligned using hydrodynamic focusing under steady-flow conditions. A key challenge will be to maintain sufficiently high interference visibility despite the presence of absorbing glass substrates and water.

5 Acknowledgments

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6 Literature

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