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Highly-efficient fully-fiberized mid-infrared differential frequency generation source and its application to laser spectroscopy

K. Krzempek*, G. Dudzik, A. Hudzikowski, A. Gluszek, K. Abramski

Faculty of Electronics, Laser & Fiber Electronics Group, Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370, Wroclaw, Poland

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ABSTRACT

Widely-tunable, fully-monolithic, mid-infrared (mid-IR) deference frequency generation source (DFG) is presented. By using a custom designed fiber-pigtailed periodically poled lithium niobate (PPLN) crystal module the *idler* beam was generated with an efficiency of 21%/W, yielding 2.6 mW of optical output power. The proposed all-fiber configuration radically simplified the optical frequency conversion setup, making it robust and easily configurable. The usefulness of the constructed source was verified by performing simultaneous wavelength modulation spectroscopy (WMS) laser trace gas detection of methane, near 2999 cm^{-1}, and ethane, near 2997 cm^{-1}, via two independently generated, tunable *idler* beams.

Introduction

Laser sources operating in the mid-infrared (mid-IR) wavelength region have been in the spotlight for the last decade, receiving a lot of attention from the laser community. This lead to their rapid development and simultaneously a great amount of research papers being published, focusing on physical principles of operation, production process improvement and applications. The ongoing thrive of mid-IR laser sources is mainly driven by the fact that the wavelength region of their operation is rich in strong fundamental vibration and associated rotational-vibrational absorption bands of many molecules [1]. This fact connected with the recent rapid technological progress in robust, low-power laser sources capable of targeting those absorption bands triggered the development of selective and sensitive laser spectroscopy-based sensors [2–6]. A relatively narrow spectral region, spanning between 3 and 3.5 μm is particularly interesting, because it holds strong fingerprints of hydrocarbons – e.g. methane, ethane acetylene and others [7–9]. Implementing laser-based detection techniques in that particular wavelength region requires a coherent source that can be swept across the target analyte. Experimental realizations of such sensors include using intraband cascade lasers (ICL) diodes [10–12], frequency conversion-based sources [13–15] or recently developed fiber-based sources [16]. Each approach has their pros and cons. The ICL's are compact and relatively easy to combine in laser spectroscopy setups, but at the same time provide a limited tuning range. Therefore, simultaneous detection of more than one target analyte usually requires using independent laser sources, each specifically tailored to a chosen molecule transition [17]. This complicates the sensor layout and multiplies the cost of deployment. The frequency conversion-based laser sources are a well-developed branch of mid-IR coherent sources. Despite known for their complexity, have been widely used in spectroscopy applications. Mainly due to their flexibility, very wide tuning range and the possibility of using fiber-based lasers as *pump* and *signal* sources, proving to be an alternative for semiconductor-based lasers [18]. DFG-based mid-IR sources capable of generating radiation in the 3.4 μm wavelength region are particularly interesting, due to the fact, that the nonlinear frequency generation process can be easily achieved by mixing 1 μm and 1.5 μm waves in widely available periodically poled lithium niobate (PPLN) crystals. The beams required in the nonlinear process can be delivered by non-complex and efficient fiber-based sources, using erbium (Er) and ytterbium (Yb) doped active fibers. The down-side of standard, bulk crystal-based DFG sources is the poor efficiency. Achieving several miliwats of *idler* beam requires Watt-level *signal* and *pump* beams being delivered to the crystal structure [14]. Moreover, complex optical setups are required for appropriate input beam shaping and coupling into the crystal, thus air-tight housing is a necessity to prevent contamination in an out-of-lab operation.

In his paper we report on a DFG-based mid-IR laser which is free of the most common drawbacks listed above. The proposed source is fully-monolithic, widely-tunable, highly-efficient, requires minimal number of optical components and is using emission of simple and inexpensive all-fiber lasers in the frequency mixing process. By incorporating a custom-designed fiber-coupled PPLN module the

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* Corresponding author.
E-mail address: karol.krzempek@pwr.edu.pl (K. Krzempek).

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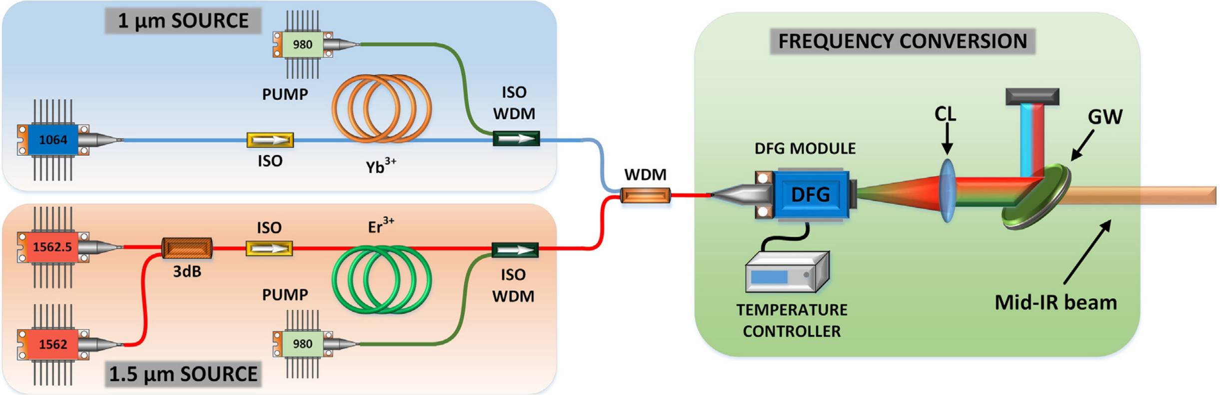

Fig. 1. Experimental setup of the fully monolithic, widely tunable all-fiber mid-IR source. 1562, 1562.5, 1064–DFB seed laser diodes (with wavelength as stated on the component), 980–980 nm, 600 mW singlemode pump diode, ISO – fiber isolator, ISO WDM – hybrid fiber component, Er^{3+} – 20 cm long active fiber doped with erbium ions, Yb^{3+} – 20 cm long active fiber doped with ytterbium ions, WDM – wavelength division multiplexer, DFG – difference frequency generation module, CL – collimating lens, GW – germanium window. All fiber components and fibers were polarization maintaining.

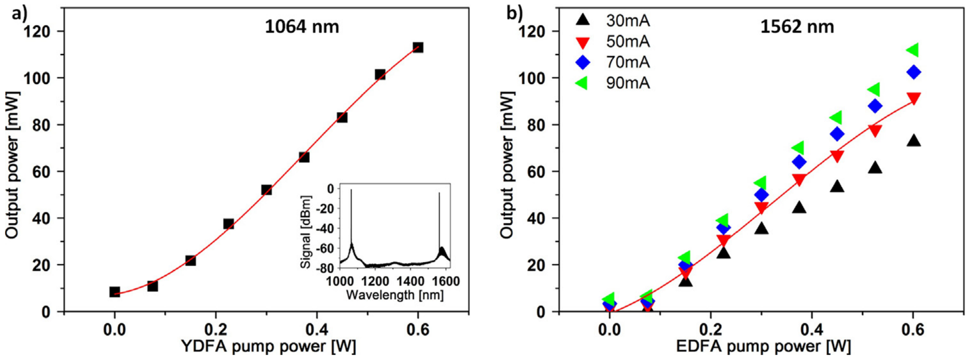

Fig. 2. Output power of both fiber amplifiers used in the experiment plotted in function of pump power delivered to the active fiber. Plot a) shows the performance of the YDFA with an inset presenting the optical spectrum registered after the WDM coupler, at maximum pump power delivered to both amplifiers. Plot b) shows output power of EDFA for 4 different 1562 seed input powers (currents set at the laser driver).

number of optical components required in the setup was reduced to a single lens collimating the *idler* output beam and a germanium filter. The proposed design reach a conversion efficiency of 21%/W, due to the waveguided (WG) structure of the PPLN crystal enclosed in the fiber-coupled frequency conversion module, at the same time reducing long-term power instabilities.

The usefulness of the constructed all-fiber mid-IR source was tested by setting-up a wavelength modulation spectroscopy-based (WMS) sensor capable of simultaneously targeting methane (CH_4) and ethane (C_2H_6) transitions, located at 2999 and 2997 cm^{-1}, respectively.

Mid-infrared source architecture

Experimental setup of the widely-tunable, fully-fiberized mid-IR source is depicted in Fig. 1. It can be divided into two main sections – low power near-IR seed sources and fiber amplifiers and the frequency conversion section. The DFG process in PPLN crystals requires the input beams to be linearly polarized. The nonlinear conversion efficiency strongly depends on the precision of polarization vector orientation in respect to the crystal axis. Any drift of this orientation or deviation from linear polarization will result in output power drop. Because the proposed mid-IR source will be tested in a laser spectroscopy configuration, any fluctuation of the output power would be considered as a noise source. Thus, the entire source has been constructed using widely available polarization maintaining (PM) fibers and components, which minimize polarization instability issues.

The optical beams used in the frequency conversion were delivered from standard, distributed feedback (DFB) seed laser diodes. We have used three diodes lasing at 1064 nm (referred as *pump* beam in the frequency conversion process), 1562 nm and 1562.5 nm (referred as *signal* beams), respectively. Separate seed diodes at the 1.5 um wavelength region were used to generate independently tunable and modulated *idler* mid-IR beams, which will later be used to simultaneously target strong absorption lines of ethane and methane. The emission of those lasers was combined via a PM 3 dB fiber coupler and coupled into an Er-doped fiber amplifier (EDFA) to boost the output power. Similarly, the 1064 nm diode was amplified in an Yb-doped fiber amplifier (YDFA). Both amplifiers were built in a standard linear amplifier configuration. The seed light was coupled through an isolator to a wavelength division multiplexer (WDM) which also coupled a 600 mW, 980 nm singlemode pump laser diode to the active fiber (both active fibers were 20 cm long). The WDM couplers were of a filter-type. The pump beams were reflected back to the active fibers, forming backward-pumped configurations, for both amplifiers. Each amplifier was terminated with a second isolator, preventing any back-scattered light distorting their operation. The seed diodes and the pump diodes were controlled by an all-in-one current and temperature controllers (Thorlabs CLD 1015). Outputs of EDFA and YDFA were combined in a single fiber via a PM-WDM coupler designed for 1 um and 1.5 um light. The performance of both amplifiers is shown in Fig. 2, where output power was plotted in function of pump power delivered to the amplifier (measured with Thorlabs S401C power meter after the WDM coupler). Insets show optical spectrum registered at