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Widely tunable, high optical signal-to-noise ratio erbium-doped photonic crystal fiber laser suitable for acetylene sensing

Min Zhang [a,b,c,d,*], Xuesen Zhong [a,b,c,d], Wanjun Zheng [e], Shuangchen Ruan [a,b,c,d], Bin Du [a,b,c,d], Peiguang Yan [a,b], Huawei Liang [a,b,c,d], Chengxiang Liu [a,b,c,d], Ling Li [a,b,c,d], Hong Su [a,b,c,d]

[a] *Shenzhen Key Laboratory of Laser Engineering, Shenzhen University, Shenzhen 518060, China*
[b] *Key Laboratory of Advanced Optical Precision Manufacturing Technology of Guangdong Higher Education Institutes, Shenzhen University, Shenzhen 518060, China*
[c] *Guangdong Provincial Key Laboratory of Micro/Nano Optomechatronics Engineering, China*
[d] *Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, Shenzhen University, Shenzhen 518060, China*
[e] *Guangdong Polytechnic of Science and Technology, Zhuhai 519090, China*

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A B S T R A C T

Narrow line-width fiber lasers are useful in gas-sensing, but systems that are both tunable and stable are rare. Here, we describe a single-wavelength ring cavity erbium-doped photonic crystal fiber laser (ED-PCFL) that can align the acetylene (C_2H_2) gas absorption peak with high precision and a maximum deviation less than 0.012 nm. Rather than using a combination of erbium-doped fiber and a strong nonlinear fiber, ED-PCF was used as a gain medium to achieve a stable single-wavelength output based on the nonlinear polarization rotation effect (NPR). This was selected because ED-PCF has a strong nonlinear effect. We added the dual polarization controllers (PCs) to weaken the homogeneous broadening based on the traditional tunable filter (TF) filtering structure. The results show that these steps improve the tunability of the laser wavelength and enhance the stability of the light source. The final laser had a side-mode suppression ratio as high as 60 dB over 45 nm with a maximum fluctuation in wavelength less than 6 pm. The peak power standard deviation was ~0.03 dB during the 2 h experimental time. The peak power response of ED-PCFL was studied as a function of C_2H_2 concentrations, and the calculated R-squared value was 0.993. This means that the ED-PCFL is suitable for C_2H_2 sensing.

1. Introduction

Narrow linewidth fiber lasers have high optical coherence, low noise, good system performance, and good sensing sensitivity [1–4]. They are used to monitor oil pipelines, in fiber optical communication, and optical fiber sensing. Various approaches are used to obtain narrow linewidth fiber lasers. These include a short linear cavity for distributed Bragg reflector (DBR) fiber lasers [5–7] and distributed feedback (DFB) fiber lasers [8,9]. Researchers have also inserted a saturated absorber in the ring structure [10,11] or the compound-ring cavity [12,13]. A special fiber Bragg grating (FBG) can also be introduced as an ultra-narrow pass-band filter [14,15].

Recently, narrow linewidth tunable fiber lasers have attracted great attention because they offer the largest signal for fiber optic gas sensing. A widely tunable Er:Yb-doped fiber laser based on a commercially available low loss tunable filter (TF) has been reported. This was combined with an adjustable output-coupling ratio [16]. Lin et al. [17] combined a TF and a nonlinear semiconductor optical amplifier. They created a tunable and stable single frequency oscillating laser output that is 48 nm wide and is based on the spectral narrowing effect caused by anti-four-wave mixing. The Yb-doped Q-switched narrow-linewidth fiber laser has spectral tunability over more than 12 nm from 1038 to 1050 nm using an acousto-optic modulator and multimode interference filter (MMIF) in the linear bulk cavity resonator [18]. In addition, the narrow linewidth laser light source power stability directly affects the sensitivity of the optical fiber gas sensing.

Han et al. [19] combined a fiber grating Fabry-Perot etalon, FBG, and high erbium-doped fiber. The laser fluctuation is less than 0.5% over 2 h. The 3 dB linewidth is less than 0.01 nm. This system is discretely tunable and the fluctuation of the output power is less than 0.1 dB. The fiber ring laser is based on the matching of the transmission spectra of two fiber Bragg grating Fabry-Perot (FBG-FP) filters [20].

In our previous report [21], an erbium-doped photonic crystal fiber (ED-PCF) distributed feedback loop laser was operated at 1550.08 nm. Two matched FBGs were used as the selective

* Corresponding author at: Shenzhen University, Shenzhen 518060, China.
E-mail address: zhangmin@szu.edu.cn (M. Zhang).

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wavelength components in the loop laser. The ED-PCF can effectively inhibit the erbium ion's self-gain broadening at room temperature, and the peak power maximal fluctuation is only 0.06 dB within 30 min. We improved our device to achieve better performance by substituting TF. A polarization-dependent isolator was used for two matched FBGs to achieve narrow linewidth lasing.

During the pursuit of maximum signal, most quartz-enhanced photoacoustic spectroscopy (QEPAS) studies currently use DFB or quantum cascade lasers that emit high power density as the light source. Thus, the light source is perfectly aligned with the strongest absorption peak of the target gas. However, explosions or toxic gases often contain a variety of gases. Therefore, to detect more than two flammable gases, one needs more DFB or a more expensive quantum cascade laser as the light source. This greatly increases the cost of detection and is not conducive to a universal trace gas sensor. Fig. 1 shows the simulation of acetylene (C_2H_2) absorption based on the HITRAN 08 database. The 3-dB linewidth of the gas absorption peak is about 0.03 nm. However, the tunable step length of the existing narrow linewidth tunable fiber laser is usually larger than 0.2 nm. Given these problems, it is necessary to develop a tunable step length less than 0.03 nm that is wide-tuning with a narrow linewidth laser operating near the gas absorption peak. This can then serve as a light source for photoacoustic spectral sensing.

In this report, we describe an extremely stable yet widely tunable system with a tunable step length less than 0.02 nm, a high optical signal-to-noise ratio (OSNR), and a narrow linewidth ED-PCFL. Systems with and without two PCs were analyzed to investigate the effects of the polarization state on laser linewidth compression and peak power stability. The system with two PCs has a narrower linewidth and a more stable power output.

2. Experimental setup and principles

2.1. Materials and methods

The experimental setup of the proposed ED-PCF loop laser is shown in Fig. 2. The ED-PCFL configuration consisted of a 10-m long, Er^{3+}-doped total-internal-reflection single-mode (SM) PCF as a gain medium. This was pumped with a 980 nm laser diode.

This system used a manually adjustable and polarization insensitive variable bandwidth tunable filter (TF). It is centered from 1525 to 1570 nm and has a continuously adjustable bandwidth of 1 to 18 nm. A polarization-dependent isolator (PD-ISO) combined the two PCs. This induces polarization-dependent loss and weakens homogeneous broadening of the ED-PCF. It also linearly polarizes the light.

The PD-ISO ensures unidirectional oscillation to force the laser to run in the traveling wave state. This avoids gain spatial hole burning effect. A 10% laser is extracted through one optical coupler (OC) for measurement. An optical spectrum analyzer (OSA, Yokogawa Electric Corporation, AQ6370B) with a spectral resolution of 0.02 nm and ranging from 600 to 1700 nm is used for optical analysis of the output signal.

The cross-section micrograph of ED-PCF is shown in Fig. 3 [21]. The ED-PCF has a similar hexagonal holey cladding with a numerical aperture of 0.143 and doping concentration of erbium ions up to 1000 ppm. The air hole diameter and hole pitch are 2.0 μm and 4.0 μm, respectively. Its fiber solid core diameter is 4.0 μm. It has an absorption coefficient of ~5.5 dB/m at 980 nm with a 3.34-μm mode field diameter. The ED-PCF stimulates a strong nonlinear effect. Its function is equivalent to a combination of gain medium and high nonlinear fiber. To evaluate stability, we investigated

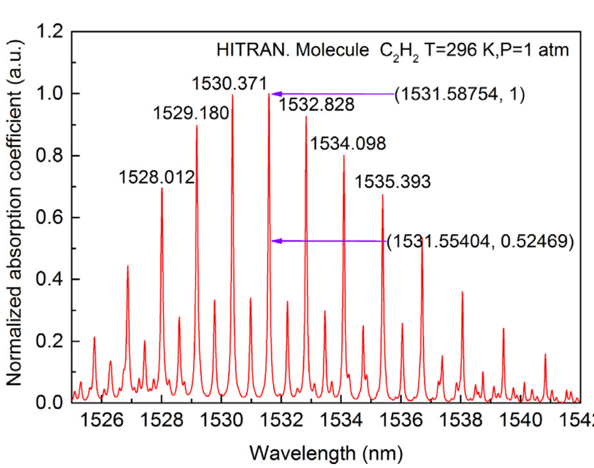

Fig. 1. HITRAN simulation of C_2H_2 normalized absorption coefficient at 296 K and standard atmospheric pressure. The absorption peak of C_2H_2 from 1527 to 1536 nm is indicated. The 3 dB linewidth of the gas absorption peak is about 0.03 nm. It is necessary to develop a tunable step length less than 0.03 nm that is wide-tuning with a narrow linewidth laser operating near the gas absorption peak. This can then serve as a light source for photoacoustic spectral sensing.

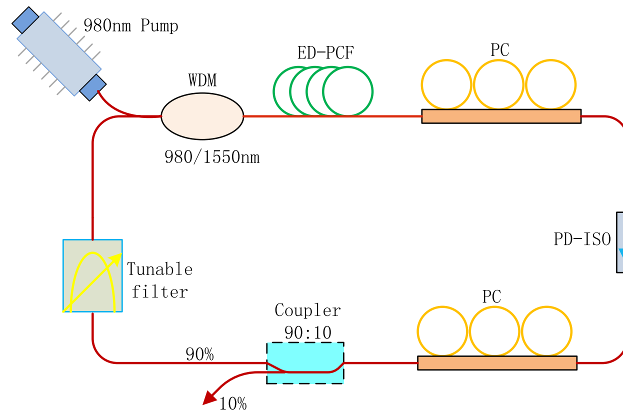

Fig. 2. Experimental configuration of the proposed narrow linewidth ED-PCFL: WDM, wavelength division multiplexer; ED-PCF, erbium-doped photonic crystal fiber; PC, polarization controller; PD-ISO, polarization dependent isolator; Tunable filter (TF) is centered from 1525 to 1570 nm and has a continuously adjustable bandwidth of 1 to 18 nm; a 10% laser is extracted through one optical coupler (OC) for measurement. PD-ISO combined the two PCs. This induces polarization-dependent loss and weakens homogeneous broadening of the ED-PCF. In addition, the PD-ISO ensures unidirectional oscillation to force the laser to run in the traveling wave state. This avoids gain spatial hole burning effect. The filter acts as a wide tuner, and the PCs act as a fine tuner.

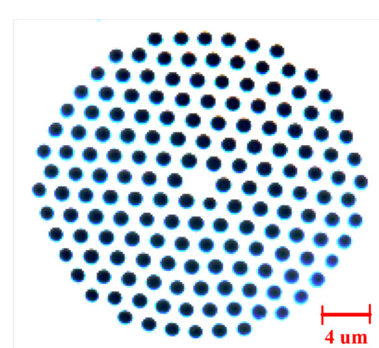

Fig. 3. This figure shows cross-section micrograph of ED-PCF [21]. The ED-PCF has a similar hexagonal holey cladding with a numerical aperture of 0.143 and doping concentration of erbium ions up to 1000 ppm. The air hole diameter and hole pitch are 2.0 μm and 4.0 μm, respectively. Its fiber solid core diameter is 4.0 μm. It has an absorption coefficient of ~5.5 dB/m at 980 nm with a 3.34-μm mode field diameter. The ED-PCF stimulates a strong nonlinear effect.