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Research Article

Broadband Degenerate Femtosecond OPO around 2060 nm

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We demonstrate a broadband degenerate femtosecond optical parametric oscillator (OPO) around 2060 nm. Synchronically pumped by a commercially available 75.6 MHz Yb:KGW femtosecond laser, it is able to generate self-phase-locked 2 μm pulses with 82 mW output power and 3 dB bandwidth of 105 nm. The degenerate operation is naturally stable in free-running condition, with only 0.8% rms fluctuation in 3.5 hours. We also obtain broadband spectrum extending from 1600 nm to 2500 nm with the 3 dB bandwidth of 452 nm by increasing the intracavity power density.

1. Introduction

Femtosecond sources in the range of 2 μm, which is close to the strong water absorber lines, are of great interests for numerous applications, such as "eye-safer" remote sensing [1], high harmonic generation [2], and driven particle acceleration [3] as well as optical frequency combs [4]. For the optical frequency comb in particular, extending it to wavelength around or beyond 2 μm is attracted for a variety of applications including coherent molecular spectroscopy [5] and trace gas detection in the fingerprint region [6], however, which still faces technical challenging. Currently, there are several methods to generate ultrafast 2 μm pulses including mode-locked solid-state lasers based on Tm or Ho doped crystal [7, 8], Tm-doped fiber lasers [9], and nonlinear parametric process [10, 11]. Among them, degenerate femtosecond optical parametric oscillator (OPO) can clearly transpose near-IR frequency combs to the mid-IR, for example, transfer the properties of a frequency comb based on commercial Yb laser to the 2 μm wavelength range. In addition, a synchronically pumped OPO operated at degeneracy not only provides phase and frequency locking of the mid-IR comb lines to the pump but also results in enhanced bandwidth. Hence, degenerate femtosecond OPO is a simple approach to generate coherent and broadband mid-IR frequency combs and has been demonstrated at several different pump wavelengths ranging from 775 nm to 4 μm [12–16]. In 2012, Rudy et al. report generation of 48 fs pulses around 2070 nm from a degenerate OPO; however the average output power is only ~10 mW [17].

In this letter, we report the demonstration of a broadband degenerate femtosecond OPO synchronically pumped by a commercially available Yb:KGW femtosecond laser. With a 3 mm long magnesium oxide-doped, periodically poled, lithium niobate crystal (MgO:PPLN), self-phase-locked pulses with average output power of 82 mW are obtained, whose spectrum has a 3 dB bandwidth of 105 nm. By further improving the intracavity power density, as broad as extending from 1600 nm to 2500 nm spectrum with 3 dB bandwidth of 452 nm is also achieved.

2. Experimental Setup

Figure 1 is an illustrative view of the experimental setup of the degenerate OPO. The pump source is a commercial KLM Yb:KGW laser (Light Conversion, FLINT6.0), which can deliver 90 fs pulses at 1030 nm with up to 7 W average power. The repetition rate of the Yb:KGW laser is 75.57 MHz, corresponding to the linear cavity length of 1985 mm. We used a 3 mm-long 5 mol% MgO doped PPLN with single grating period of 31 μm as the nonlinear crystal. It is antireflective-coated at 1035 nm ($R < 0.5\%$) and 2070 nm ($R < 0.5\%$) on

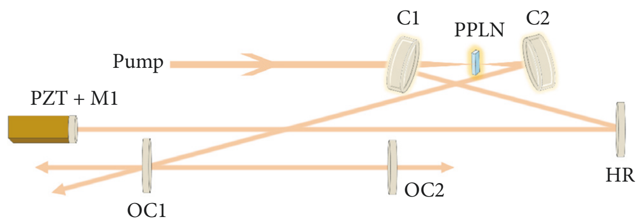

Figure 1: The sketch for the experimental setup of the degenerate OPO. C1 and C2: concave mirrors with ROC of 150 mm; HR: flat mirror with high reflectivity; M1: sliver mirror; PZT: piezo translator; OC1 and OC2: output couplers.

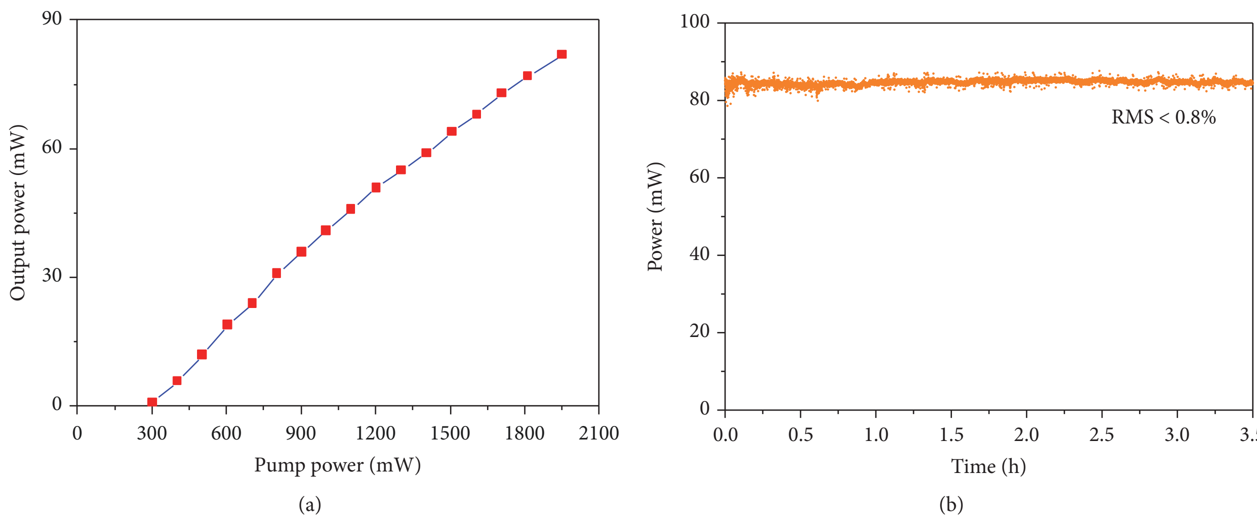

Figure 2: (a) Power scalable of the OPO output at degeneracy. (b) Long-term power stability of the maximum output power of the degenerate OPO.

both surfaces. Because that the phase matching of degenerate operation for such a PPLN with 31 μm grating period is realized at the temperature of 94°C, we used an oven to heat the MgO:PPLN, which can also limit the amount of photorefractive damage caused by the strong 1 μm pump. To eliminate the harmful influence on the Yb:KGW laser from reflected pump and signal, the pump laser was firstly through an isolator comprising an half-wave-plate (HWP), a polarization beam splitter (PBS), and an Faraday rotator (FR). The combination of the HWP and PBS also acted as a power attenuator, keeping the pump power focused on the PPLN less than 2 W to avoid damage on the PPLN. We used the second HWP after the FR to adjust the pump polarization relative to the crystal orientation. C1 and C2 are two concave mirrors with 150 mm radium of curvature (ROC), coated with high reflectivity over 1900–2100 nm ($R >$ 99.9%) and high transmittance around 800–1200 nm ($R <$ 10%). HR is a flat mirror with high reflectivity in the region of 1850–2200 nm ($R > 99.9$). M1 is a sliver mirror, on which a piezo translator (PZT) was mounted to finely tune the cavity length. Two output couplers (OC) were used in the cavity, leading to output in three channels, which is convenient for monitoring or further locking. OC1 has the transmittance of 20% around 1700–2700 nm and OC2 is a 0.5 mm long broadband pass filter (BBP-1660–2250 nm) with 80% transmittance from 1660–2250 nm. The linear cavity was about 1.98 m long in length, which was matched to the pump repetition rate.

The OPO cavity could be easily aligned with the visible second harmonic generation (SHG) of the pump. After the initial alignment, we achieved successful operation of the nondegenerate OPO in free-running condition with the cavity length being finely tuned by using the PZT stage to meet the synchronous pumping condition. With further fine adjustment the cavity length or changing the temperature of the oven, OPO operation was gradually transferred to a degenerate and self-phase-locked oscillation. The output power from OC2 was dropped from 160 mW in nondegenerate operation to 82 mW in degeneracy with 2 W pump power. We measured the output power at different pump power as described in Figure 2(a). As evident, the output power linear increases with the pump power, and the threshold for degenerate operation was about 300 mW. As shown in Figure 2(b), we also measured the long-term stability of the output power at degeneracy, which was with a fluctuation of 0.8% rms in 3.5 hours, indicating that the degenerate OPO was naturally stable so that a feedback servo loop is not necessary. The fluctuation was mainly derived from the ambient temperature fluctuation, airflow, and mechanical vibration.

We performed the spectral characterization of the OPO output in near-degenerate and degenerate operation with a

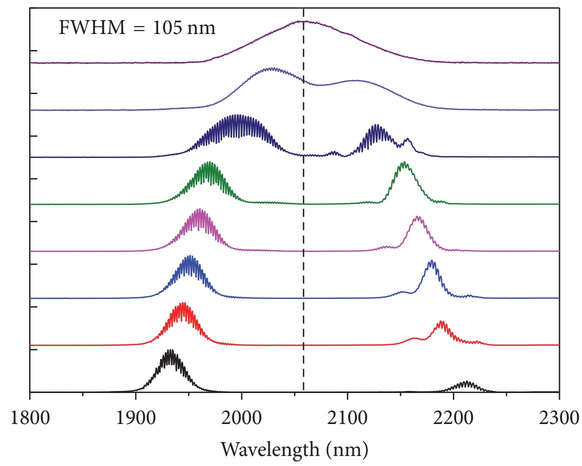

Figure 3: Spectra evolution from the near-degenerate operation to the degeneracy of the OPO. Dash line: the degenerate point.

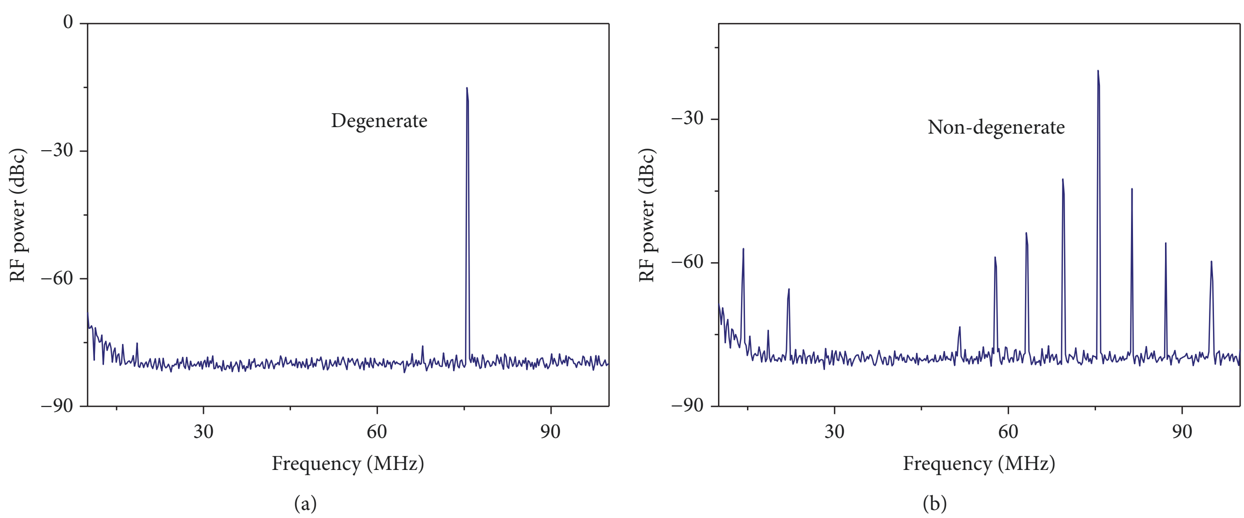

Figure 4: RF spectra of the degenerate and near-degenerate OPO with resolution bandwidth of 10 kHz, respectively.

commercial wavelength-meter (WaveScan, A. P. E GmbH), as presented in Figure 3. It is obvious that the OPO output spectra undergo a gradual transition from near-degenerate operation to an exactly degenerate state when increasing the cavity length. In near-degenerate operation, there are clearly two distinct signal and idler spectra, which exhibit some spiking and modulation but progressively merge into a single broadband and smooth spectrum centered at 2060 nm in degenerate operation. The full width at half maximum (FWHM) of the spectrum at degeneracy was about 105 nm, corresponding to a Fourier transform limited pulse duration of 42 fs if a sech^2 shape was assumed. However due to the lack of suitable autocorrelator, the character of the temporal profile of the degenerate pulses was not conducted.

To claim the status of the degenerate operation, the radio frequency (RF) spectra of both degenerate and near-degenerate operations were also measured via a photo detector (PD) with a 3 dB bandwidth of 1 GHz and a commercial RF spectrum analyzer (R&S FSVA40) as shown in Figure 4. At degeneracy, there is only one peak in Figure 4(a), which indicates that the signal and idler are self-phase-locked well. In the near-degenerate state, there is no stable injection locking despite the partially overlapping signal and idler spectra. This is proofed by the additional peaks in the RF spectrum (Figure 4(b)), which are contributed to the frequency beat between the overlapping tails of the signal and idler waves with different f_{ceo}.

We further investigated the relationship between the spectrum width at degeneracy and the intracavity power density, by utilizing different output couplers while maintaining the pump power. Figures 5(a)–5(d) depict the spectra characterization of the OPO output at degeneracy with different combination of OC1 and OC2. The total transmittance of OC1 and OC2 from Figures 5(a) to 5(b) tent to decrease, corresponding to the increasing of intracavity power density. Hence, it is clear to see that the spectrum of the OPO output at degeneracy is broaden as the growing of the intracavity power density, which could be attributed to the self-phase modulation. For Figure 5(d) case, the spectrum covered from 1600 nm to 2500 nm, with the FWHM of 452 nm.

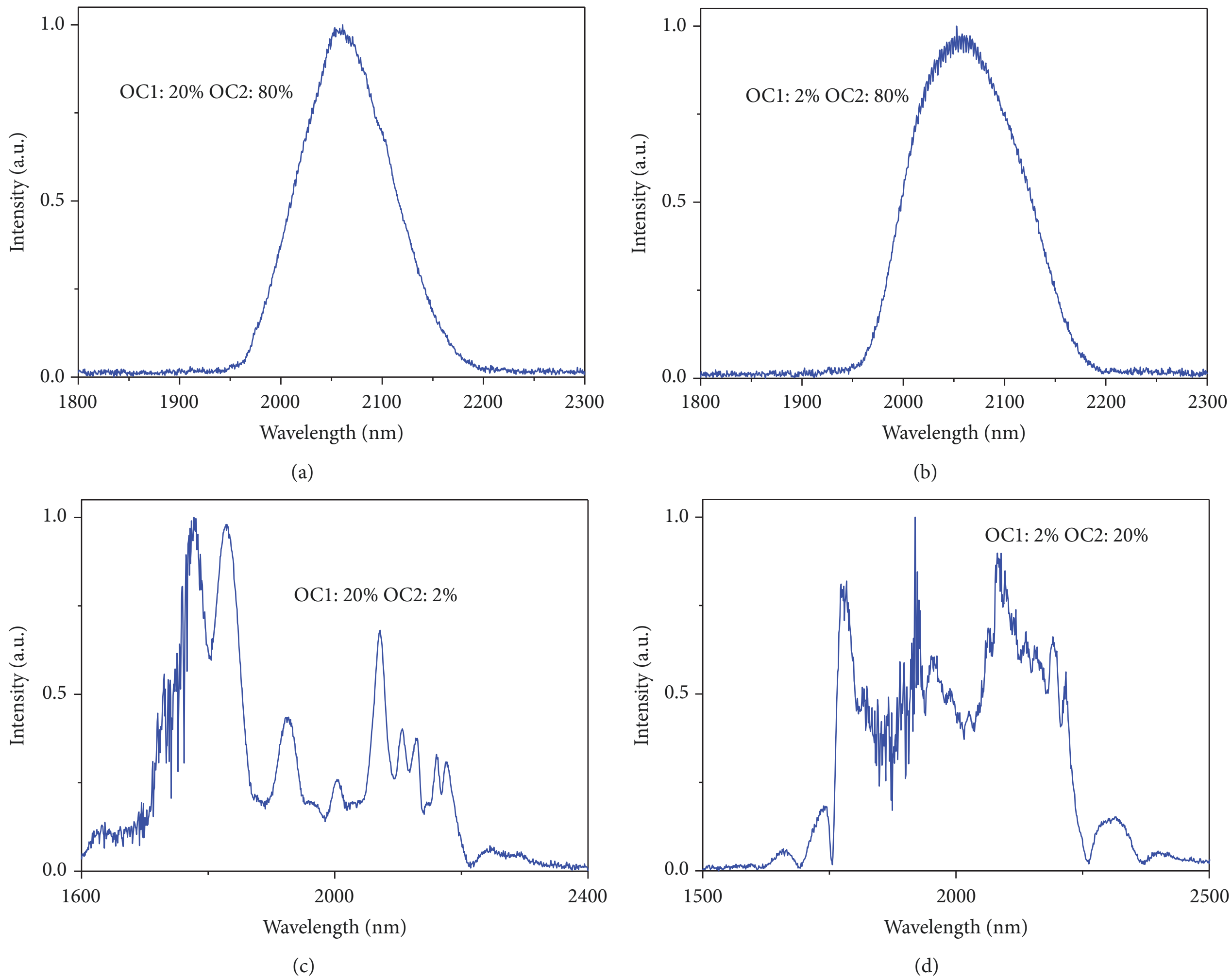

Figure 5: Spectra of the degenerate OPO with different output couplers.

3. Conclusion

In conclusion, we experimentally demonstrated a degenerate synchronically pumped OPO based on MgO:PPLN, generating 2 μm pulses with 82 mW average power. The spectrum of 2 μm pulses has a FWHM of 105 nm, which could support as short as 42 fs pulse duration. Without active stabilization, the degenerate OPO can be naturally stable with only 0.8% rms fluctuation in 3.5 hours. By further improving the intracavity power density, degenerate pulses with as broad as covering the region of 1600–2500 nm spectrum were successfully obtained. Since the mid-IR pulses are phase-locked to the pump laser, such broadband femtosecond source is very suitable for midinfrared frequency comb and well found lots of applications in various fields.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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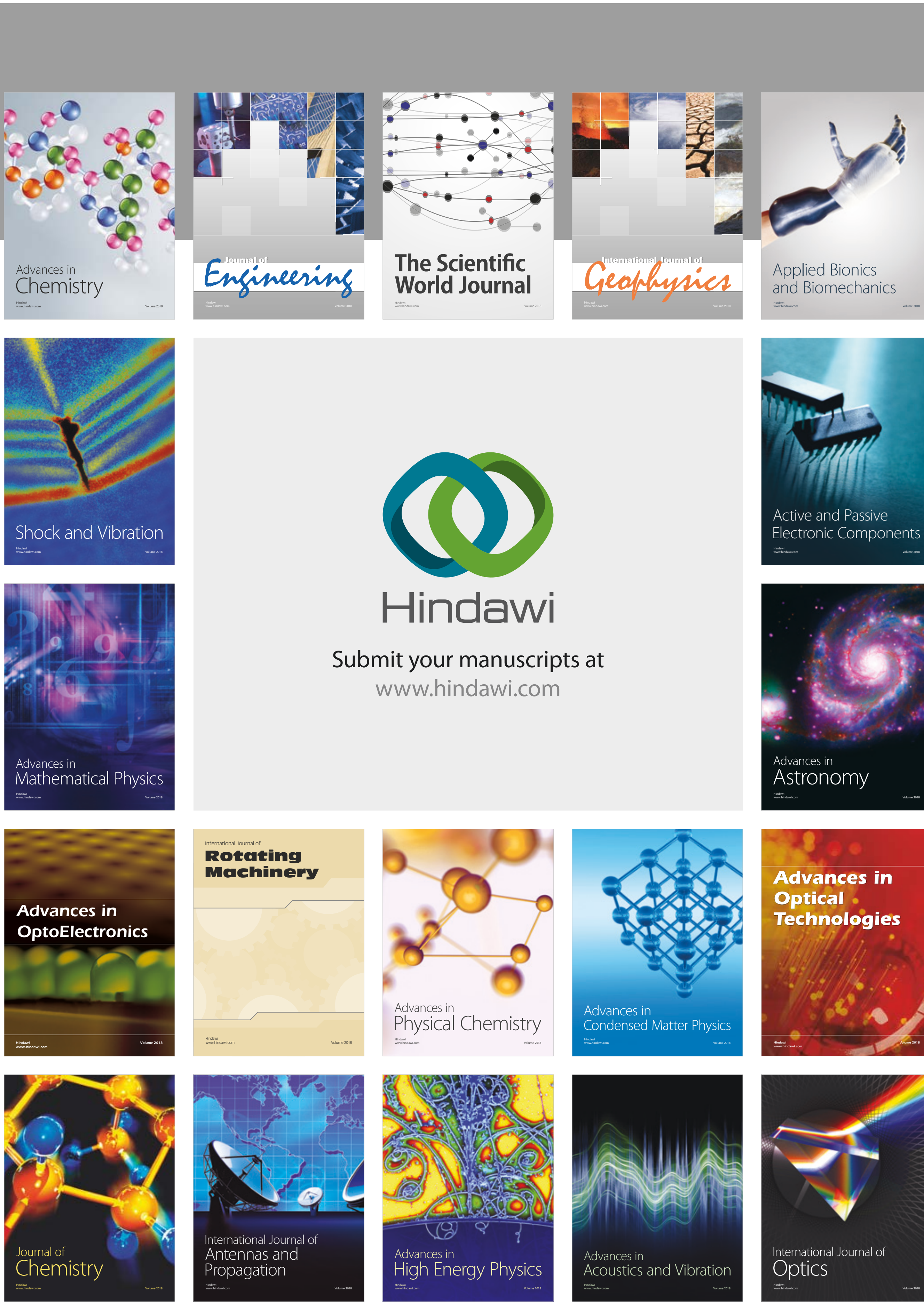
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