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Millimeter wave generation for 6G applications through supercontinuum spectrum in highly nonlinear fibers with an SOA-based ring cavity laser system

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The development of 6G wireless networks aims to provide high-speed, low-latency communication, with millimeter-wave frequencies (from 30 to 300 GHz) crucial for enabling high-capacity communication. These frequencies offer significant bandwidth but present challenges in signal generation and processing. A promising solution is the use of supercontinuum (SC) generated in highly nonlinear fibers (HNLF), the nonlinear optical process which creates broad spectral outputs spanning multiple frequency bands. HNLFs, with their high nonlinearity and dispersion properties, facilitate wideband optical spectra when subjected to high-intensity pulses. In this study, we explore supercontinuum generation using a semiconductor optical amplifier (SOA) to produce high-intensity pulses at 1550 nm, injected into a 4-meter-long HNLF. The proposed system generates a supercontinuum spectrum with average power of 31 dBm and peak pulse width of 0.008 ps, spanning from 1529 nm to over 1570 nm. The SOA in the ring cavity is optimized to generate supercontinuum without needing an external laser or pump source. The HNLF output is then detected by a photodetector to produce millimeter-wave signals. The system generates signals over a 1 GHz–5 THz range, with an output power of 39.9 dBm at 30 GHz, making it self-sustaining without an external laser.

Keywords: supercontinuum generation, highly nonlinear fiber (HNLF), semiconductor optical amplifier (SOA), millimeter wave generation.

1. Introduction

The rapid evolution of wireless communication technologies has led to the emergence of 6G, a new frontier in mobile networks that promises unprecedented speed, ultra-low latency, and massive connectivity. The millimeter-wave technology offers vast bandwidth, enabling the high data rates and low-latency communication necessary for the diverse applications anticipated in the 6G era. However, the generation of millimeter -wave signals presents significant challenges due to the high-frequency nature of the waves, which are prone to propagation losses, limited range, and sensitivity to environmental factors. SOAs compensate for network losses and hence expand the network reach. SOAs feature numerous important characteristics, including significant nonlinearities, minimal power consumption, wavelength adaptability, vast dynamic range, rapid response, broadband and agile functioning, compact dimensions with the potential to be embedded in a single chip, and a relatively low cost [1-4]. To fully realize the potential of millimeter-wave for 6G, advanced techniques and novel technologies are required for efficient generation, transmission, and reception of these high-frequency signals. This includes the development of new materials, devices, and architectures that can operate at these higher frequencies, ensuring seamless, reliable communication across the network. In this study, we propose an SOA-based ring cavity laser system for supercontinuum generation using the nonlinear effects in highly nonlinear fiber (HNLF), the output spectrum of which is used to generate the desired millimeter-wave with the aid of a photodetector.

Supercontinuum generation is an instance of integrating nonlinear effects to create incredibly wide optical spectra. Light of extremely high intensity can be pumped into any nonlinear medium to generate a supercontinuum. Due to their ability to efficiently control heat and confine high power light over long distances, optical fibers (including photonic crystal fibers (PCFs), tapered fibers, HNLFs, and standard telecom fibers) are frequently utilized as the preferred nonlinear medium. Consequently, a supercontinuum (SC) source with equalized spectra, extended bandwidth, high power, high brightness, and beam quality is produced [5].

Self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), four-wave mixing (FWM), and other high-order nonlinear effects are among the several nonlinear effects that contribute to the spectrum broadening [6]. The preferred fiber for producing the SC spectrum is HNLF and the optimized semiconductor optical amplifier (SOA) in conjunction with the HNLF may produce the SC spectrum at a wavelength of approximately 1550 nm. A range of techniques using multiple pump or laser source along with several meters long HNLF and expensive components has been demonstrated for supercontinuum generation as indicated in Table 1.

Similarly, an assortment of techniques has been proposed for generating millimeter -wave signals, involving direct intensity modulation, optical heterodyne, optical external modulation, and frequency multiplication [7-12]. To the best of our knowledge, modulators remained obligatory for every millimeter-wave generation scheme including the frequency multiplication technique, which leads to the degree of system com-

Table 1. Comparison of supercontinuum generation schemes.

Reference	External laser source	Fiber length
Prakash *et al.* [5]	Seed laser	300 m HNLF, 1 km large effective area fiber, 7 m Er-Yb doped fiber
Chang [13]	Seed laser	8 cm HNLF, 2 m photonic crystal fiber (PCF), 0.6 m erbium doped fiber (EDF), 3 m dispersion compensating fiber (DCF)
Turnali *et al.* [14]	Three pump sources at 1565 nm Laser diode at 793 nm	100 m and 140 m HNLF comparison
Meng *et al.* [15]	Pump source at 976 nm	10.3 m HNLF, 11 m EDF, 2.87 m single mode fiber (SMF), 4.45 m and 7.80 m SMF
Luo *et al.* [16]	Laser source at 1480 nm	102 m HNLF, 6.6 m EDF, 10 m DSF, 10 m SMF
Hadi *et al.* [17]	Laser diode	50 m HNLF, 1.8 m EDF
Lauterio-Cruz *et al.* [18]	Three pump sources at 980 nm	3 m EDF1, 2 m EDF2, 100 m DCF, different lengths of SMF and HNLF
Lauterio-Cruz *et al.* [19]	Pump source at 980 nm	100 m HNLF, 10 m SMF, 200 m HNLF
Xia *et al.* [20]	Laser diode at 980 nm	110 m HNLF, 20 m EDF, 0.9 m SMF
Lin *et al.* [21]	Two pump laser diodes at 976 nm	1 m HNLF, 0.6 m EDF, 3 m DCF, 1.2 m EDF
Ahmad *et al.* [22]	Two laser diodes at 1480 nm	100 m HNLF, 49 bismuth-erbium doped fiber (Bi-EDF)
Proposed scheme	–	4 m HNLF

plexity. The objective of this research is to minimize the number of microwave sources required for future 6G networks in remote locations while addressing dynamic frequency requirements. While RF frequency generation based on Mach–Zehnder modulators has already been reported, such implementations necessitate a laser source, an oscillator, and a modulator significantly increasing the overall cost. In contrast, this research proposes the use of a ring cavity laser with a SOA as the gain medium and a HNLF to enhance the nonlinear effects. This approach inherently reduces the system cost to approximately one-fourth of the conventional setup and the SOA provides a dynamic gain mechanism to enhance RF signal power by adjusting the bias current. Based on this intriguing approach, supercontinuum spectrum spanning from 1529 nm to more than 1570 nm has been generated without the aid of any pump or laser source. SOAs are a desirable option for our work, where reducing system complexity and cost is the primary concern, due to their affordability when compared to other optical amplifiers like EDFAs, which need an additional pump or laser source, and their simplicity of integration into the systems.

2. Numerical model

The key question is what mechanism generates the nearly flat, broad supercontinuum seen in Fig. 5(a). The answer lies in the combined effects of SPM, SRS, and FWM. Initially, SPM broadens the pulse spectrum, and SRS further extends it on the red side via cascaded Raman scattering. Subsequently, multiple Raman bands serve as pumps, generating Stokes and anti-Stokes bands symmetrically. It is important to note that some of the Stokes components fall within the anomalous-GVD region of the fiber, which allows for the formation of solitons. At higher pump powers, their peak power increases enough to generate new sidebands via modulation instability. The position of these FWM-induced sidebands shifts further from the pump as the power increases. Additionally, interactions between multiple spectral bands through XPM and SRS contribute to the creation of the nearly flat supercontinuum [23]. A generalized nonlinear Schrödinger equation has been effectively used to explain many of the observed features in the propagation of high-power pulses through fibers [24]. The equation

$$\frac{\partial E(z,t)}{\partial z} = -\frac{\alpha}{2}E - \left[\sum_{m=2} \beta_m \frac{i^{m-1}}{m!}\frac{\partial^m}{\partial t^m}\right]E + i\gamma(1-f_R)\left[|E|^2E - \frac{2i}{\omega_0}\frac{\partial}{\partial t}(|E|^2E)\right] + i\gamma f_R\left\{1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\left[E\int_0^\infty h_R(t')|E(z,t-t')|^2\,\mathrm{d}t'\right]\right\} \tag{1}$$

accounts for the effects of linear loss and dispersion (the first and second terms on the right-hand side of Eq. (1)), self-phase modulation and self-steepening (the third and fourth terms), and the delayed Raman effect (the final term). It is solved using a modified split-step method. In this equation, $E(z,\ t)$ represents the electric field as a function of propagation distance z and time t, α denotes the linear loss, β_m are the linear dispersion coefficients, γ is the effective nonlinearity, and ω_0 is the center angular frequency. The relative contributions of the instantaneous and delayed Raman effects are represented by f_R, and the Raman response function is given by $h_R(t)$ [23].

3. Operating regimes in a semiconductor optical amplifier structure

The saturation power of SOA is a vital variable that affects both linear and nonlinear features to attain the maximum gain. It comes from CONNELLY [25]:

$$P_{\mathrm{sat}} = \frac{A}{\Gamma} I_{\mathrm{s}} \tag{2}$$

In this case, A represents the cross-section area of the active zone, Γ is the optical confinement factor coefficient, and I_{s} is the saturation intensity, which is determined by

$$I_{\mathrm{s}} = \frac{h\nu}{a_{\mathrm{N}}\tau} \tag{3}$$

where h is Planck's constant, ν is the optical frequency, a_{N} is the differential modal gain, and τ is the spontaneous carrier lifetime.

In order to increase the saturation output power, the injection current must be increased, as a low bias current results in less gain and lower saturation output power. Additionally, the optical confinement factor should be decreased, as it is inversely proportional [26]. Accordingly, the injection current of SOA has been raised from its default value of 0.13 to 0.45 A and the optical confinement factor has been decreased to 0.4, as indicated in Table 2, producing extremely intense amplified pulses. By adopting this approach, during the first loop, the noise output from the SOA is selectively converted into a signal and used as the input for the second loop. This process continues, enabling the SOA to amplify signals around 1550 nm continuously. Subsequently, a coupler picks up these pulses after HNLF and routes them to an isolator for preventing undesired back reflections, making a closed loop structure as shown in Fig. 1. The output of the coupler is then detected by a photodetector. The band-pass filter (BPF) can be used to pick any wave from the millimeter waves that make up the output.

T a b l e 2. Optimized SOA parameters.

Parameter	Values
Injection current	0.45 A
Input facet reflectivity	5×10^{-5}
Output facet reflectivity	5×10^{-5}
Active length	0.6×10^{-3} m
Width	0.4×10^{-6} m
Height	0.4×10^{-6} m
Optical confinement factor	0.4
Recombination coefficient	360×10^{6} s^{-1}
Group velocity	75×10^{6} m/s
Temperature	300 K

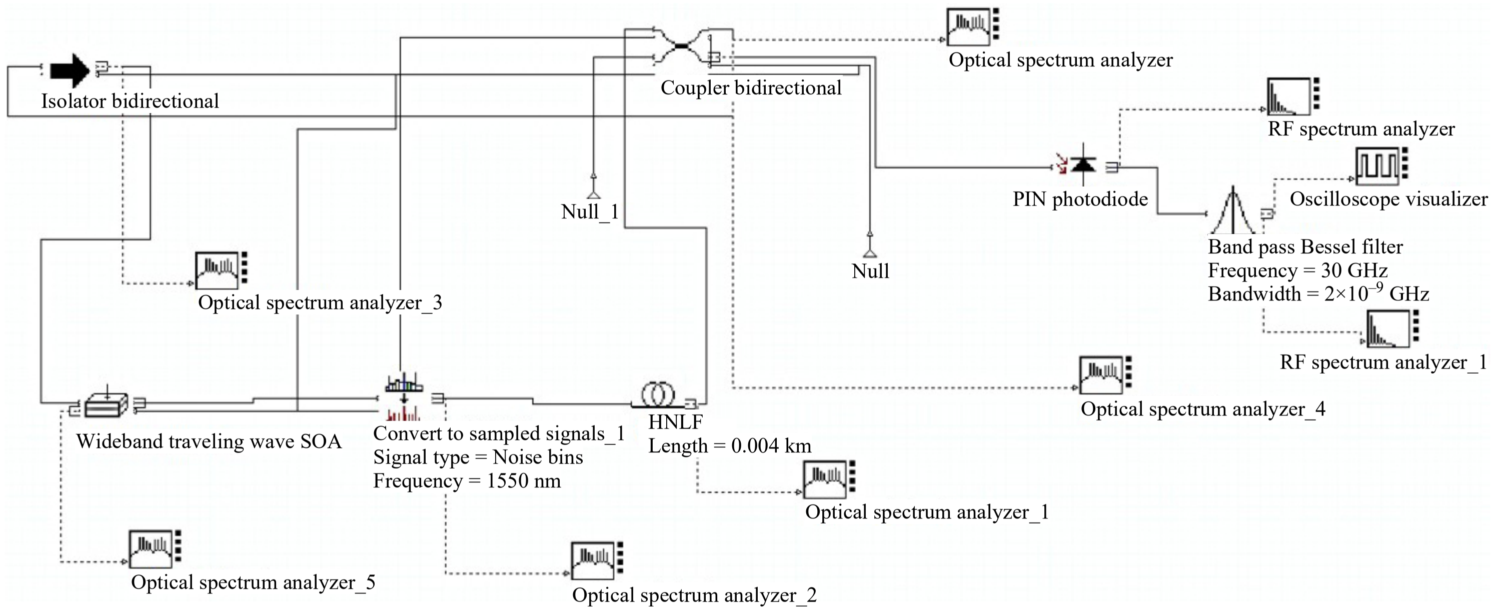

Fig. 1. Simulation setup of SOA-based millimeter-wave generation system.

4. Simulation and results

The simulation setup of an SOA-based millimeter-wave generation system is depicted in Fig. 1. The parameters of optimized SOA are given in Table 2. The signal from the optimized SOA is fed into the HNLF with a length 4 m. The SOA along with the convert noise to sampled signals component (for simulation purpose), HNLF, isolator, and coupler forms the closed-loop system, the output of which is subsequently detected by the PIN photodiode.

Nonlinear effects in the SOA such as self phase modulation (SPM), cross-phase modulation (XPM) and gain saturation have been carefully considered. The SOA is operated at its optimal bias range to mitigate excessive nonlinear distortions while ensuring efficient amplification. Signal loss due to insertion of equipment and possible reflection are overcome by the gain provided by SOA. Here the isolator ensures that the light travels from the input port to the output port with minimal loss while preventing any reflected light from traveling back into the input port. This isolation is essential for maintaining the stability and performance of optical devices and systems. It is evident from Fig. 2 that as the pulse progresses down the HNLF, new frequency components are constantly being generated and the spectrum has broadened beyond its original width. It is predicted that an optimized SOA can attain peak gain and produce highly intense pulses with additional frequencies when coupled to an optical fiber such as HNLF to produce nonlinear effects. In a typical ring cavity simulation setup, a seed

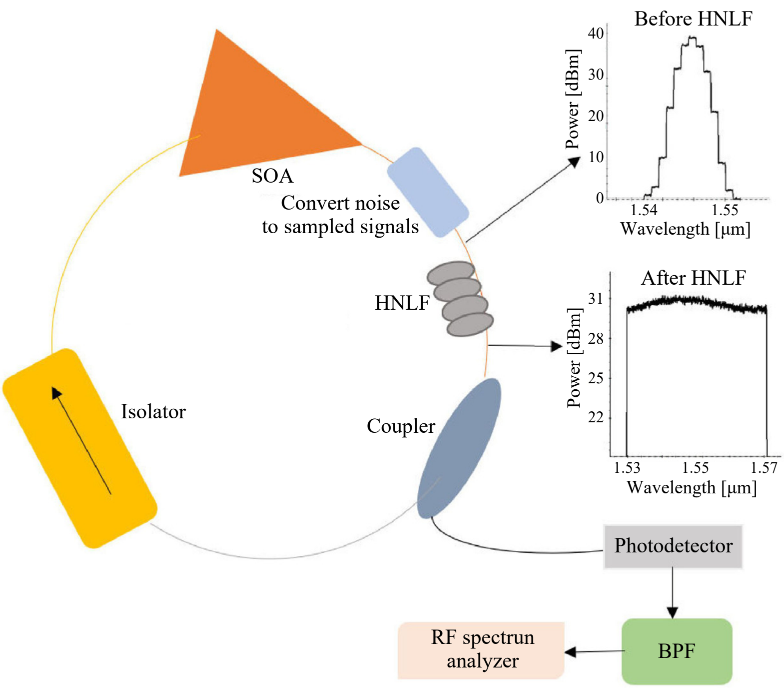

Fig. 2. Simulation setup with HNLF output of SOA-based millimeter-wave generation system.

signal is introduced into the loop to define the intended wavelength range. However, in our simulation setup, to achieve a more realistic representation, no seed signal has been introduced. Instead, the noise generated by the SOA is converted into a signal, providing a better understanding of the simulation process. This converted signal is then reapplied to the SOA, as illustrated in Fig. 1.

The spectrum before HNLF and the spectrum following HNLF are depicted in Figs. 3(a) and (b), respectively. Also, Fig. 3(b) demonstrates the spectral broadening induced by the nonlinear effects after it passes through the 4 m long HNLF as indicated in Table 3. A wide range of signals, from 1 GHz to 5 THz, has been generated, as

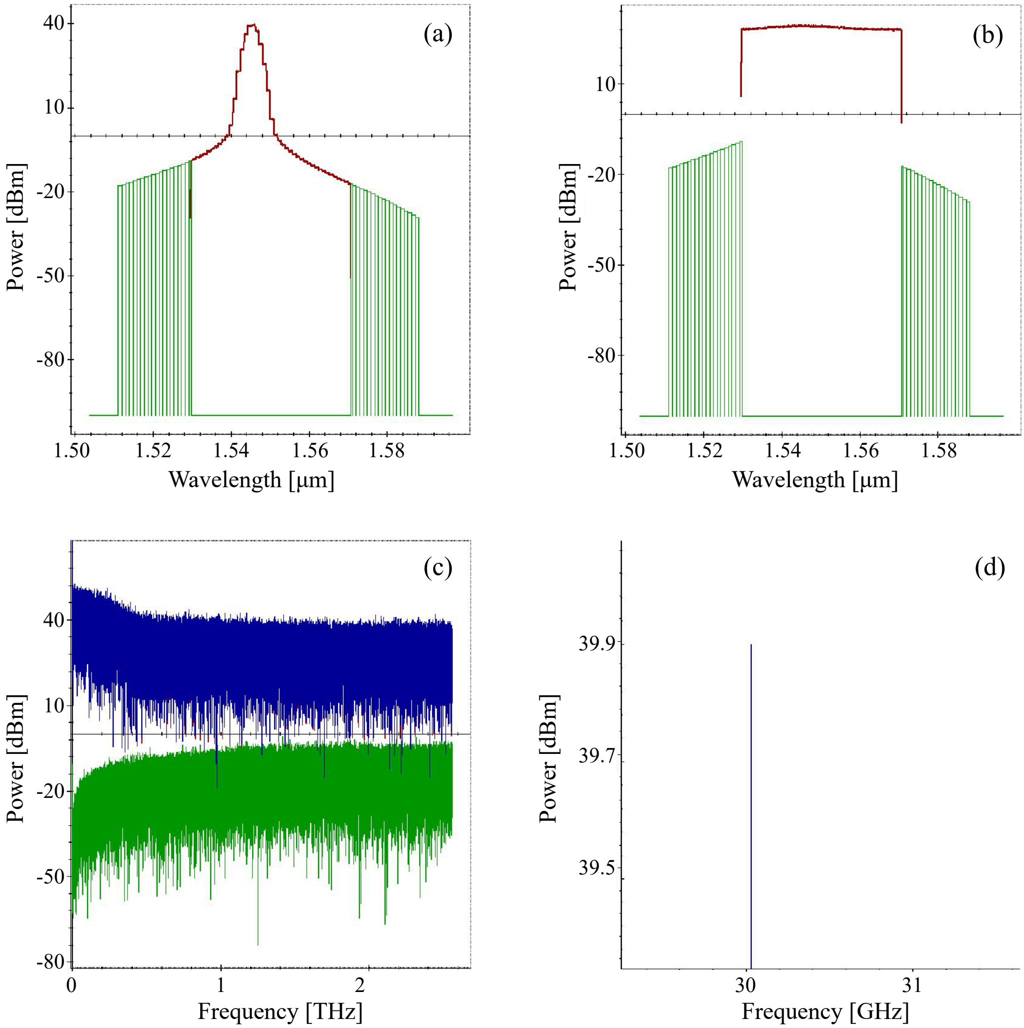

Fig. 3. Millimeter-wave generation system's (using HNLF) optical and electrical spectrum (a) before HNLF, (b) after HNLF, (c) after PD, and (d) after BPF.

T a b l e 3. HNLF parameters [27].

Parameter	Value
Length	4 m
Attenuation	1.847 dB/km
Dispersion	−0.1 ps/nm/km
Effective area	11.5 μm^2
Dispersion slope	0.0074 ps/nm^2/km
Nonlinear parameter n_2	35.46 × 10^{-21} m^2/W
Zero dispersion wavelength	1550 nm

shown in Fig. 3(c), the output spectrum of the photodetector. To adopt the desired frequency signal, a bandpass filter is utilized. Based on the findings of the simulation, our suggested scheme can generate a 30 GHz millimeter wave with a high power of about 39.9 dBm as shown in Fig. 3(d).

Figure 4 presents the supercontinuum spectrum generated as the amplified pulse propagates through the HNLF for different values of SOA injection current and it can

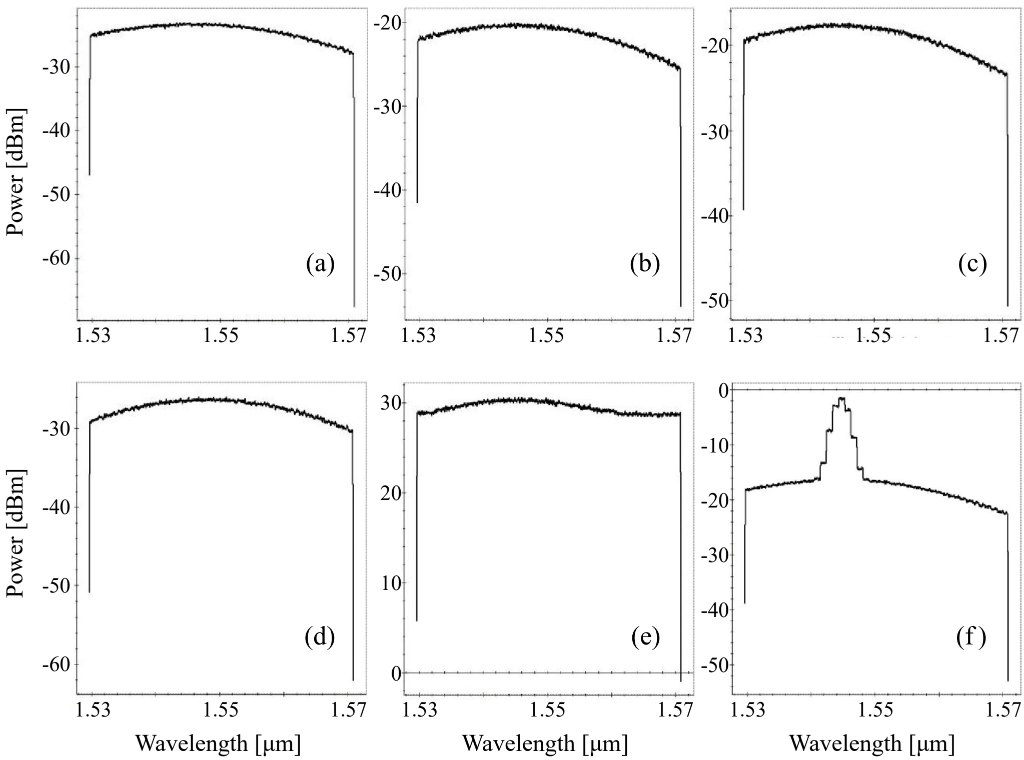

Fig. 4. Continued on next page.

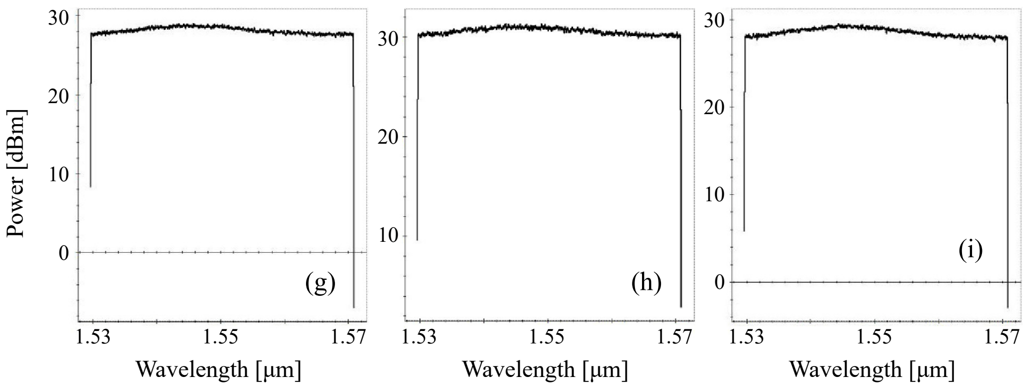

Fig. 4. SC spectra for different values of SOA injection current: (a) 0.1 A, (b) 0.15 A, (c) 0.2 A, (d) 0.25 A, (e) 0.3 A, (f) 0.35 A, (g) 0.4 A, (h) 0.45 A, and (i) 0.5 A.

be seen clearly that the equalized spectra with an average high power of about 31 dBm is obtained for the injection current of 0.45 A as depicted in Fig. 4(h) above which the power begins to drop down as shown in Fig. 4(i).

Figure 5(a) presents the simulation result of SC generation by launching amplified pulses into a 4 m HNLF and Fig. 5(b) represents the temporal profile of the peak pulse of the generated SC spectrum having a pulse width of 0.008 ps. As shown in Fig. 5(a), the simulated SC spectra have a spectral range of approximately from 1529 to 1570 nm, without any external laser or pump source, thereby confirming the feasibility of the proposed scheme.

The evolution of the spectrum for different lengths of highly nonlinear fiber (HNLF) is shown in Fig. 6, where it is clearly observed that as the length of the HNLF in-

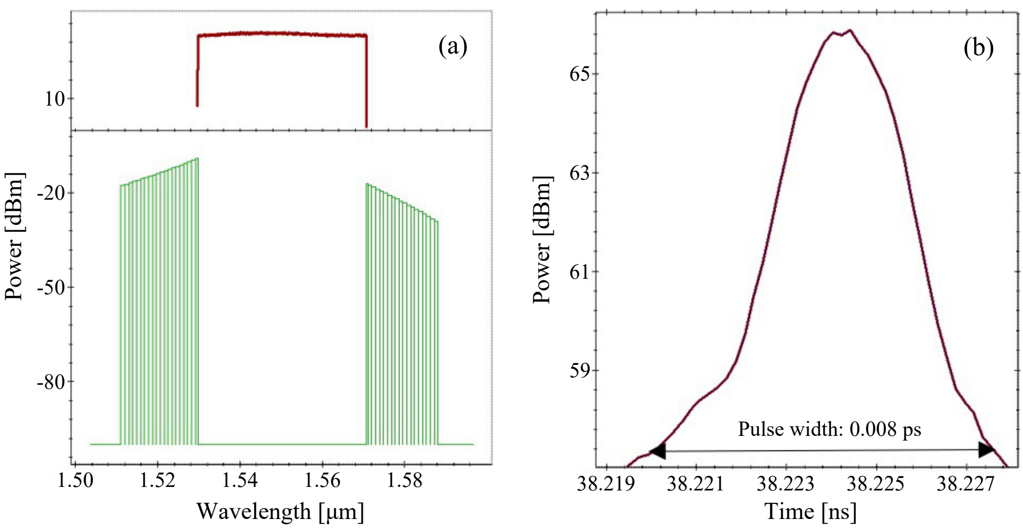

Fig. 5. (a) SC spectra, and (b) temporal profile of the peak pulse.

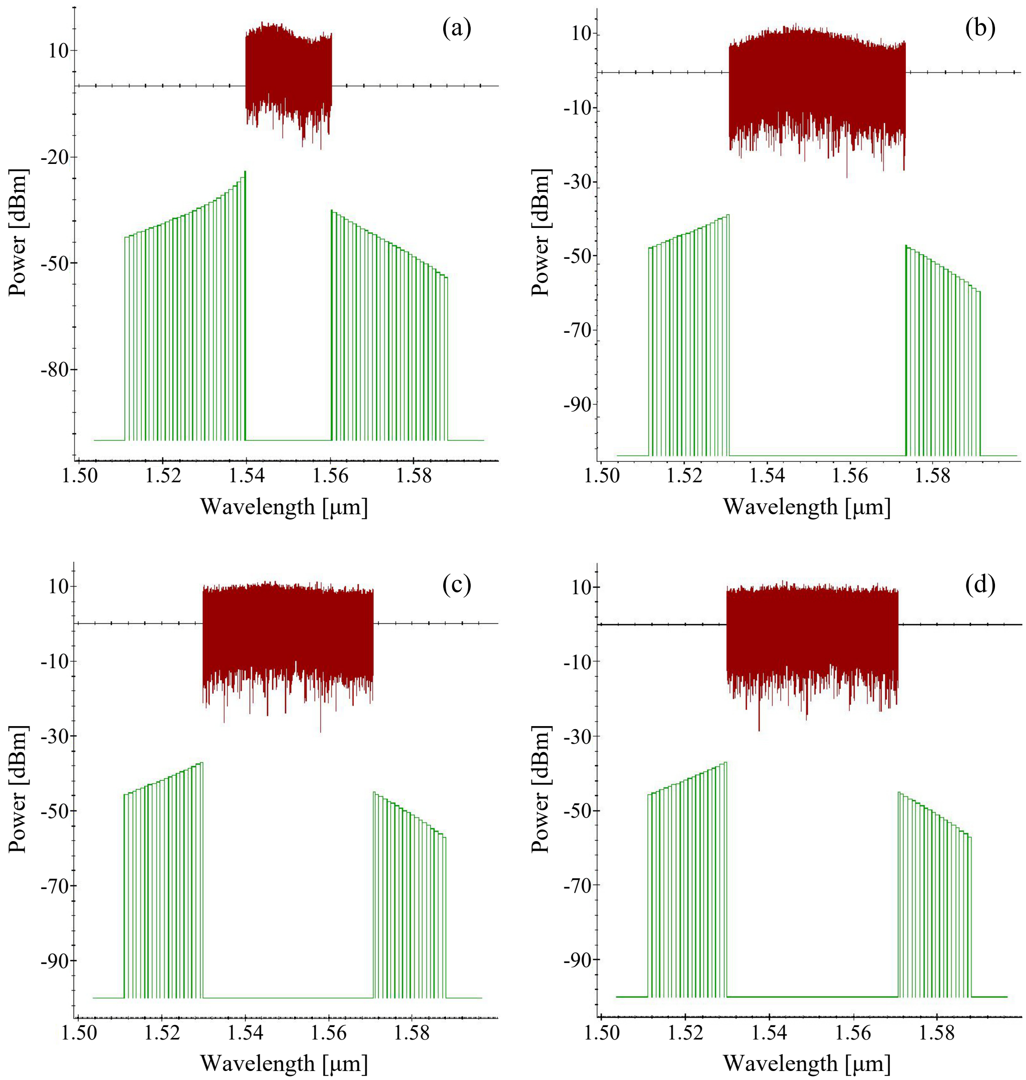

Fig. 6. Evolution of spectrum for various HNLF lengths: (a) 1 m, (b) 2 m, (c) 3 m, and (d) 4 m.

creases, the spectrum undergoes a progressive broadening and flattening. This change is symmetric, with the spectral energy spreading equally on both sides of the central frequency peak. This behavior suggests that the nonlinear effects, such as self-phase modulation (SPM) and four-wave mixing (FWM), become more pronounced over longer fiber lengths, causing the generated new frequency components to spread out more evenly across the spectrum.

The evolution of supercontinuum (SC) spectra across various schemes from contemporary research is presented in Fig. 7. In Fig. 7(a), Chang *et al*. [13] showed simulated

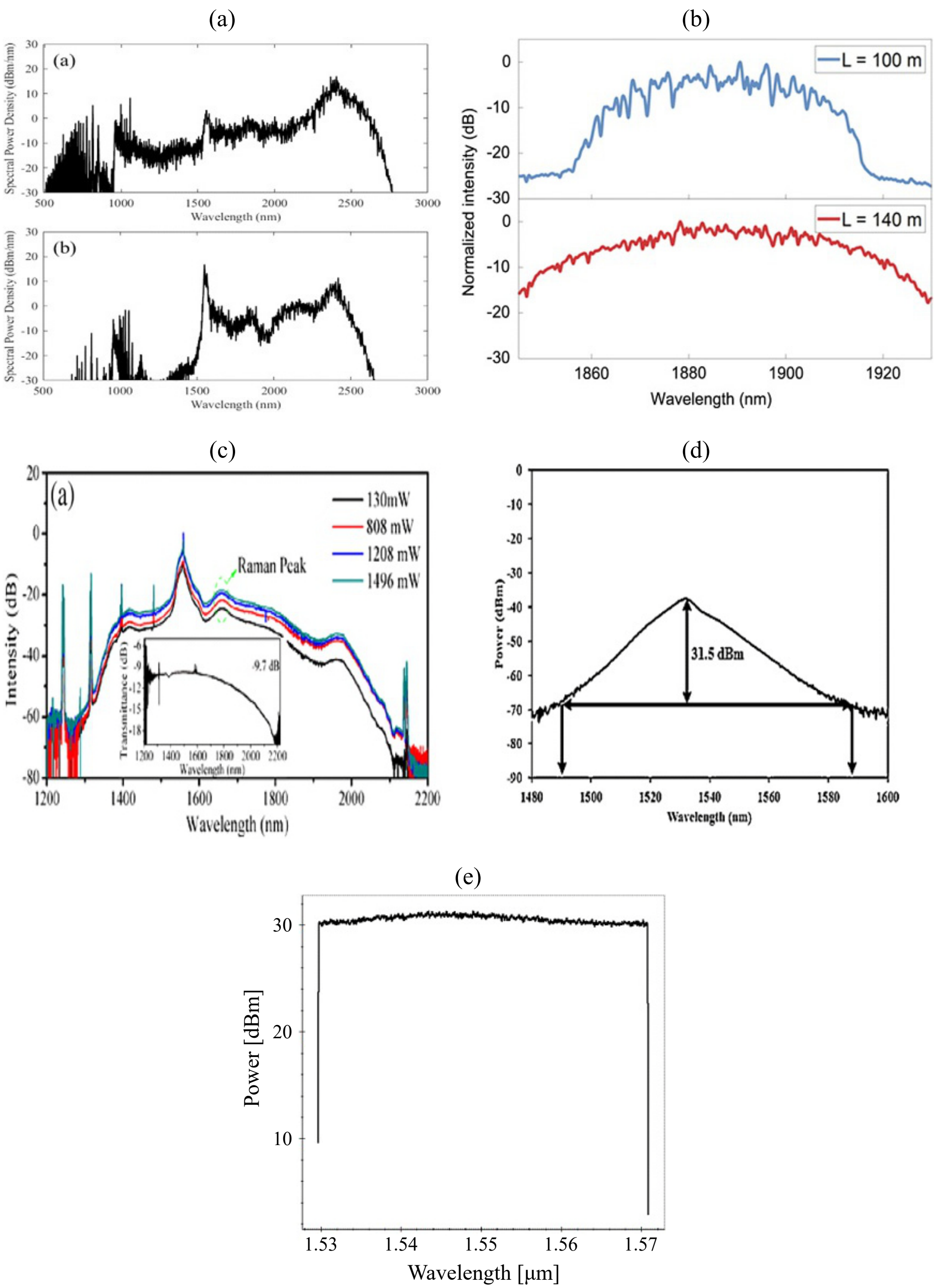

Fig. 7. SC spectra. (a) CHANG *et al.* [13], (b) TURNALI *et al.* [14], (c) LUO *et al.* [16], (d) HADI *et al.* [17], and (e) proposed scheme.

optical spectra of supercontinua generated by (a) noise-like pulses (NLPs) and (b) pre-chirped well-defined pulses (WDPs) at the output of different hybrid nonlinear fibers. The SC generated by launching amplified NLPs into an 8 cm HNLF and 2 m PCF has a spectral power density above –20 dBm/nm from 520 nm to 2.25 μm. When amplified pre-chirped WDPs were pumped into the same fiber, the SC has a spectral power density above –20 dBm/nm from 680 nm to 2.25 μm. In Fig. 7(b), TURNALI *et al.* [14] presented the optical spectra of noise-like pulses (NLPs) generated in 100-meter-long (NLP-I, blue, top) and 140-meter-long (NLP-II, red, bottom) nonlinear fibers, which exhibited 3-dB bandwidths of 17.7 and 26.6 nm, respectively [14]. In Fig. 7(c) LUO *et al.* [16] depicted the measured spectra of a mode-locked fiber laser which spanned from 1330 to 2030 nm with varying pump powers. In Fig. 7(d) HADI *et al.* [17] demonstrated the supercontinuum generation spanning from 1490 to 1590 nm with a bandwidth of 100 nm using 50 m long HNLF. Finally, in Fig. 7(e) the proposed scheme is illustrated, which generates a nearly flat supercontinuum with an average high power of approximately 31 dBm. Compared to the other schemes, this approach performs well by providing a flat spectrum in the range of 1529 to 1570 nm with high power, using a 4-meter-long HNLF without the need for an external or pump laser source.

5. Conclusion

In this study, an millimeter-wave generation system through the supercontinuum spectrum generated in HNLF with the aid of an optimized SOA in a ring cavity has been demonstrated. A supercontinuum spectrum spanning from 1529 to 1570 nm was produced using only a 4-meter-long HNLF, and the output of the SC generation system was subsequently detected by a PIN photodetector. With the help of the proposed scheme, signals spanning a broad range of 1 GHz–5 THz were generated without the need for any external lasers or pump sources, which would otherwise increase the system's complexity and cost. The simulation results indicate that the proposed scheme is an appropriate option for 6G applications, as it generates millimeter-wave signals with a peak power of 39.9 dBm at 30 GHz.

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