

REVIEW



Recent Advances in Nonlinear Dynamics of Fiber Lasers and Amplifiers at Near-Infrared Spectrum

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Abstract: Fiber lasers and amplifiers operating in the near-infrared III (NIR-III) spectral region, approximately 1550–1870 nm, are increasingly important for biomedical imaging, spectroscopy, optical communications, sensing, and advanced photonic systems because this wavelength range combines reduced scattering, useful tissue penetration, and compatibility with mature telecom-band fiber technology. However, direct ultrafast generation across the full NIR-III window remains difficult because erbium-, thulium-, holmium-, and bismuth-based gain media provide only fragmented gain coverage, limited efficiency, or restricted pulse-energy scaling. This review therefore focuses on how third-order nonlinear mechanisms in optical fibers overcome these gain limitations by shifting, broadening, and parametrically converting pulses from convenient pump wavelengths into the NIR-III region. Unlike general treatments of nonlinear fiber optics, the emphasis here is on NIR-III-specific design constraints: dispersion and phase matching near 1.55–1.9 μm . Raman red-shift pathways from telecom-band sources, coherence and noise requirements for biomedical imaging, and the trade-off between tunability, pulse duration, spectral power density, and system complexity. Self-phase modulation, four-wave mixing, stimulated Raman scattering, soliton self-frequency shift, and supercontinuum generation are reviewed and compared using practical performance metrics, including wavelength coverage, pulse duration, output power, pulse energy, efficiency, coherence, and implementation complexity. The review concludes by identifying key opportunities in large-mode-area, hollow-core, and dispersion-engineered fibers, as well as hybrid gain-nonlinear architectures for stable, efficient, and application-driven NIR-III fiber sources.

Keywords: fiber lasers, bismuth-doped fibers, soliton dynamics, supercontinuum generation, ultrashort pulses

1. Introduction

Fiber lasers operating in the 1550–1870 nm spectral region, commonly referred to in this review as the third near-infrared III (NIR-III) window, have attracted strong interest because they

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combine several useful optical and technological advantages. In biological tissue, longer near-infrared wavelengths generally experience reduced scattering compared with shorter near-infrared bands, which can improve penetration depth and image contrast in selected optical imaging modalities. In photonics, this spectral region also overlaps with mature telecom-band components and extends toward wavelengths useful for gas sensing, spectroscopy, nonlinear microscopy, optical coherence tomography (OCT), and free-space optical communications [1–4].

The biomedical relevance of the 1.6–1.8 μm portion of this window has also increased because longer near-infrared excitation can reduce scattering and enable deeper interrogation of biological tissue compared with shorter near-infrared bands. In multiphoton microscopy, wavelengths around 1.3 μm and 1.7 μm have been widely investigated for deep-brain and deep-tissue imaging because they provide improved penetration depth while still allowing efficient nonlinear excitation of fluorophores and contrast agents [5–10]. These studies have helped establish the 1.7 μm region as a particularly important target for ultrafast fiber-source development. As a result, the NIR-III window is not only a spectral extension of telecom photonics but also a practical wavelength range for advanced biomedical imaging, OCT, photoacoustic imaging, and spectroscopy.

The need for robust NIR-III sources, therefore, creates a connection between nonlinear fiber physics and application-driven photonic engineering. A useful source must provide not only the correct wavelength but also suitable pulse duration, pulse energy, average power, coherence, beam quality, and long-term stability. This is especially important in biomedical imaging, where source noise and wavelength instability can directly affect image contrast and quantitative reliability. Consequently, nonlinear mechanisms such as Raman shifting, soliton self-frequency shift (SSFS), parametric conversion, and supercontinuum (SC) generation should be evaluated not only as physical processes but also as source-design tools that determine whether a fiber system can meet the practical requirements of a target application [11–14].

Despite these advantages, compact ultrafast fiber sources that are widely tunable across the entire NIR-III window remain challenging. The main difficulty is not the absence of fiber-laser technology but the mismatch between desired NIR-III output wavelengths and the gain bandwidths of practical doped fibers. Erbium-doped fibers are highly mature near 1.55 μm , but their gain does not efficiently span the entire 1.6–1.9 μm

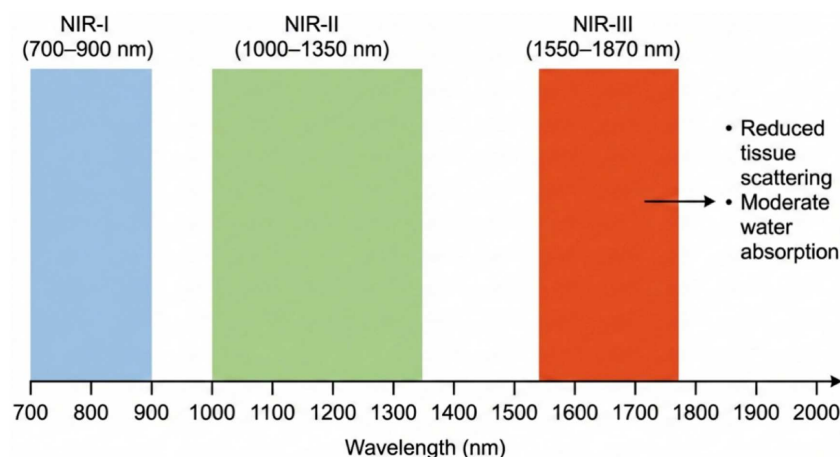
range. Thulium-, holmium-, and bismuth-doped fibers can extend emission toward longer wavelengths, but they often suffer from limited bandwidth, lower efficiency, fabrication sensitivity, amplified spontaneous emission, thermal loading, or limited ultrafast pulse energy [15–18].

Third-order nonlinear effects provide a powerful solution by separating pulse generation from wavelength conversion. In this architecture, a stable seed oscillator or master-oscillator power-amplifier system generates high-quality pulses at a convenient wavelength, often near 1.0 or 1.55 μm , and a passive or specialty nonlinear fiber then shifts, broadens, or converts the spectrum into the NIR-III band. Because silica fibers are centrosymmetric, second-order nonlinear processes are weak in standard fibers, while the third-order susceptibility, χ^3 , dominates the nonlinear response. The resulting mechanisms include self-phase modulation (SPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), SSFS, and SC generation [19, 20]. Figure 1 provides a schematic representation of near-infrared spectral windows, highlighting the NIR-III region. Figure 1 emphasizes that the 1550–1870 nm band lies between mature telecom-band fiber technology and longer-wavelength infrared applications, while also overlapping with wavelengths useful for reduced-scattering biomedical imaging.

Although nonlinear dynamics in optical fibers have been extensively described in foundational texts, their use in the NIR-III region requires a more application-specific analysis. In this window, the choice of mechanism is governed by the fragmented rare-earth gain landscape, the fiber dispersion profile near 1.55–1.9 μm , Raman-shift compatibility with telecom-band pumping, increasing sensitivity to coherence and relative-intensity noise in imaging systems, and the need to balance spectral power density with stability and all-fiber integration. Therefore, this review is not intended as a general textbook review of nonlinear fiber optics. Instead, it examines how χ^3 mechanisms are selected and engineered specifically to address the source limitations of NIR-III fiber lasers and amplifiers.

The paper is organized as follows. Section 2 summarizes the minimum theoretical background needed to connect the mechanisms to fiber-source design. Section 3 identifies NIR-III-specific design constraints. Section 4 reviews direct gain media and explains why nonlinear conversion is required. Section 5 discusses SPM, FWM, SRS, SSFS, and SC generation with emphasis on NIR-III implementations. Section 6 compares the mechanisms

Figure 1
Schematic representation of near-infrared spectral windows, highlighting the NIR-III region and the 1550–1870 nm band



quantitatively and critically, and Section 7 presents conclusions and future directions.

2. Brief Theoretical Background: $\chi^{(3)}$ Nonlinear Pulse Propagation in Fibers

Only the theoretical elements needed for the later NIR-III discussion are summarized here. Detailed derivations of nonlinear pulse propagation, Kerr nonlinearity, soliton dynamics, Raman scattering, and SC generation are available in standard references, especially Agrawal's Nonlinear Fiber Optics and Applications of Nonlinear Fiber Optics [19, 20]. Figure 2 also provides a qualitative comparison of χ^3 nonlinear mechanisms. SPM broadens the pump spectrum, FWM generates phase-matched signal and idler waves, SRS produces red-shifted Stokes components, SSFS continuously shifts soliton pulses to longer wavelengths, and SC generation combines several mechanisms to create broadband output. The figure should connect each mechanism to its typical NIR-III role: broadening, wavelength conversion, red-shifting, tunability, or broadband illumination.

2.1. Nonlinear polarization and Kerr response

In a dielectric medium, the induced polarization $P(t)$ in response to an applied electric field $E(t)$ can be written as a power series:

$$P = \epsilon_0 [\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots] \quad (1)$$

where ϵ_0 is the vacuum permittivity and $\chi^{(1)}$, $\chi^{(2)}$, and $\chi^{(3)}$ are the linear, second-order, and third-order susceptibilities of the medium [19–21]. Silica fibers possess inversion symmetry, so $\chi^{(2)} \approx 0$ and second-order effects such as second-harmonic generation are negligible. The lowest-order nonlinearity is therefore the third-order susceptibility, $\chi^{(3)}$, which gives rise to Kerr-type phenomena (intensity-dependent refractive index) and FWM [19, 20].

For a monochromatic field in a fiber, the Kerr effect is usually expressed as:

$$n(I) = n_0 + n_2 I, \quad (2)$$

where n_0 is the linear refractive index, n_2 is the nonlinear index coefficient, and I is the optical intensity. The nonlinear phase shift acquired over a fiber of effective length L_{eff} is:

$$\phi_{\text{NL}} = \gamma P_0 L_{\text{eff}}, \quad \gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}, \quad (3)$$

with γ the nonlinear parameter, P_0 the peak power, and A_{eff} the effective mode area. This phase shift is the starting point for SPM and many related effects.

2.2. Generalized nonlinear Schrödinger equation

Propagation of a slowly varying pulse envelope $A(z, t)$ in a single-mode fiber (SMF) is typically described by the generalized nonlinear Schrödinger equation (NLSE):

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} + \dots = i\gamma |A|^2 A + i\gamma T_R A \frac{\partial |A|^2}{\partial t} \quad (4)$$

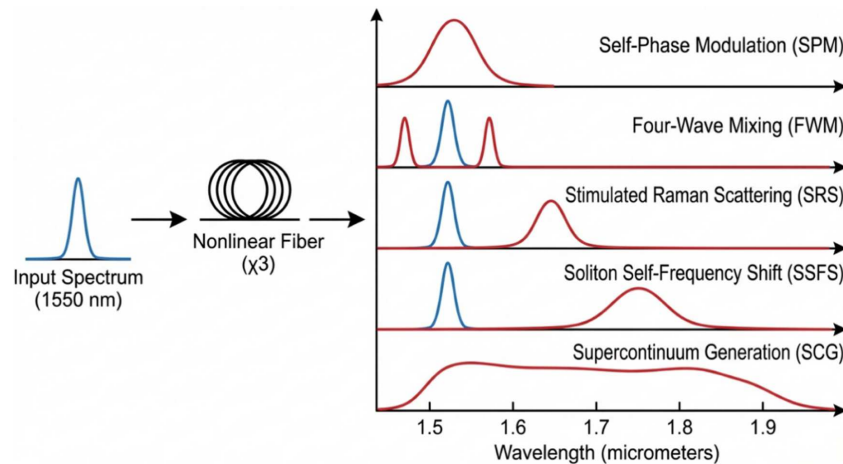
+ FWM, Raman terms,

where α is the loss, β_2 is the group-velocity dispersion, and T_R accounts for the delayed Raman response. Depending on pump wavelength and fiber design, the dispersion may be normal ($\beta_2 > 0$) or anomalous ($\beta_2 < 0$); the latter supports soliton solutions when nonlinearity exactly balances dispersion. Different terms in this equation correspond to different nonlinear phenomena: the Kerr term $i\gamma |A|^2 A$ leads to SPM and FWM, while the Raman term drives SRS and SSFS [1–15].

The individual nonlinear mechanisms discussed later can be understood as different operating regimes of this equation. SPM is dominated by the instantaneous Kerr term. FWM requires both Kerr nonlinearity and phase matching. SRS and SSFS arise from the delayed Raman response. SC generation occurs when multiple effects act together under suitable dispersion and peak-power conditions [21].

The importance of Equation (4) is that it provides a unified mathematical framework for interpreting the different nonlinear pathways used in NIR-III fiber sources. Early soliton theory showed that anomalous dispersion can balance Kerr nonlinearity and allow optical pulses to propagate while preserving their temporal shape [22, 23]. However, real fibers are not ideal soliton media. Higher-order dispersion, self-steepening, loss, gain, and delayed Raman response perturb the ideal soliton solution and

Figure 2
Qualitative comparison of χ^3 nonlinear mechanisms for NIR-III fiber source development



can shift, broaden, or destabilize the pulse. These perturbations are not merely secondary effects in the NIR-III context; they are often deliberately exploited to move energy from mature pump wavelengths into the 1.55–1.87 μm range.

The delayed Raman response is especially important because it breaks the spectral symmetry of an ultrashort pulse and transfers energy toward lower optical frequencies. This mechanism underlies both SRS and the SSFS. Gordon's theory of the SSFS showed that intrapulse Raman scattering causes soliton pulses to continuously red-shift during propagation [24]. This effect becomes stronger for shorter, higher-peak-power pulses and is therefore central to femtosecond NIR-III source design. Similarly, SPM arises from the instantaneous Kerr response and produces deterministic spectral broadening through an intensity-dependent phase shift [25]. In contrast, SRS involves energy exchange with vibrational modes of the glass and can produce discrete Stokes-shifted wavelengths when the Raman gain exceeds threshold [26, 27]. Thus, the same generalized propagation equation can describe several distinct operating regimes depending on dispersion, pulse duration, peak power, fiber length, and nonlinear response.

3. NIR-III-Specific Design Considerations

A central revision of this manuscript is the explicit recognition that nonlinear fiber dynamics are not used in the NIR-III window simply because they are interesting physical effects. They are used because this spectral region imposes source-design constraints that are difficult to satisfy with direct gain alone [18].

3.1. Fragmented gain coverage

The 1550–1870 nm region lies across the edge of several gain systems rather than at the center of one broad, efficient, mature gain band. Erbium systems are strong near 1.55 μm but become less suitable for longer NIR-III wavelengths. Thulium and holmium systems extend to longer wavelengths but often require careful pumping and suffer from efficiency and thermal constraints. Bismuth-doped fibers can cover portions of the 1.6–1.8 μm band, but performance depends strongly on fabrication conditions and active-center formation. Nonlinear conversion, therefore, provides a practical method for using robust seed lasers while reaching wavelengths outside their direct gain range [16–18].

3.2. Dispersion and phase matching near 1.55–1.9 μm

FWM, SSFS, and SC generation are strongly governed by dispersion. Around the telecom band and beyond, small changes in the zero-dispersion wavelength can substantially alter phase matching, modulation instability, dispersive-wave generation, and soliton fission. For NIR-III systems, dispersion-engineered fibers such as dispersion-shifted fibers, highly nonlinear fibers, photonic-crystal fibers, large-mode-area (LMA) fibers, and hollow-core fibers are therefore not optional details; they are often the central design element that determines whether the desired wavelength shift or bandwidth can be obtained [28–31].

The development of photonic-crystal fibers and hollow-core fibers well illustrates the importance of dispersion engineering. Photonic-crystal fibers provide additional freedom to tailor the effective index, mode area, confinement, and zero-dispersion wavelength beyond what is possible in conventional step-index silica fibers [32–34]. This is particularly useful for NIR-III

nonlinear conversion because phase matching for FWM, soliton fission, and dispersive-wave generation can be shifted by modifying the fiber geometry. In practical terms, the fiber is not simply a passive transmission medium; it is an active design element that controls which nonlinear pathway dominates.

Hollow-core and gas-filled fibers offer a different route to dispersion and nonlinearity control. By guiding light predominantly in a gas-filled core, these fibers can reduce material overlap, increase damage threshold, and introduce molecular Raman gain that is not available in solid silica fibers [35–37]. Hydrogen- or deuterium-filled hollow-core photonic-crystal fibers (HC-PCFs), for example, can support efficient Raman conversion to longer wavelengths while maintaining relatively high beam quality. Such platforms are attractive for NIR-III source development because they allow the Raman shift, dispersion, and nonlinear interaction length to be engineered simultaneously. However, they may also introduce practical complexity, including gas handling, pressure tuning, fiber coupling, and packaging challenges.

3.3. Raman red-shift compatibility with telecom-band pumps

One reason SRS and SSFS are especially attractive in the NIR-III window is that Raman red-shifting from mature telecom-band sources naturally moves energy toward 1.6–1.8 μm . For a pump near 1550 nm, the dominant silica Raman shift can move Stokes energy into the lower NIR-III region, and cascaded or soliton-based Raman effects can extend further toward 1.8–1.9 μm . This makes Er-based systems valuable pump platforms even when the final output wavelength lies beyond the efficient erbium gain band [38, 39].

3.4. Application-driven requirements

NIR-III sources are often evaluated not only by wavelength coverage but also by application-specific requirements. Biomedical imaging may require low relative-intensity noise, stable pulse trains, short pulse duration, high beam quality, and sufficient spectral power density at a selected wavelength. Spectroscopy may require tunability and narrowband brightness. OCT and broadband imaging may benefit from a broad bandwidth but can be limited by coherence noise. These competing requirements explain why no single nonlinear mechanism is universally optimal for all NIR-III applications [40].

4. Gain Media and Limitations of Direct NIR-III Fiber Lasers

Direct rare-earth and bismuth gain remains important because it can provide compact, stable, and efficient fiber-laser operation in selected sub-bands. However, direct gain alone rarely provides the combination of wide tunability, femtosecond pulse duration, high energy, and high efficiency across the entire 1550–1870 nm range. This limitation motivates hybrid architectures in which direct gain produces a stable seed or pump and nonlinear propagation provides wavelength extension [15–18]. Table 1 shows the comparative summary of direct-gain fiber media relevant to the NIR-III window.

Table 1

Comparative summary of direct-gain fiber media relevant to the NIR-III window. The table emphasizes why nonlinear wavelength conversion is usually needed for broadband ultrafast coverage of 1550–1870 nm

Gain medium	Approximate useful range	Pulse-energy trend	Efficiency trend	NIR-III strength	Main limitation
Bismuth-doped fiber [15–41]	~1650–1800	Mode-locked nJ-level reported in selected systems	Moderate, fabrication-dependent	Broad luminescence in lower/mid NIR-III	Unsaturation loss, fabrication sensitivity, limited ultrafast energy scaling
Thulium-doped fiber (TDF) [17, 18]	~1700–2000 depending on design	High energy possible in Q-switched regimes; fs energy more limited	Low to medium	Access to longer NIR-III and beyond	Thermal load, pump absorption, bandwidth and Amplified Spontaneous Emission (ASE) constraints
Thulium/holmium co-doped fiber [18]	~1700–1900	Often low in ultrafast mode-locked operation	Low to moderate	Extended emission by co-doping	ASE, limited pulse energy, complex pumping
Erbium-doped fiber [19, 20]	~1530–1620, edge overlaps NIR-III	Highly mature seed/pump platform	High near 1550 nm	Excellent stability and telecom components	Insufficient direct coverage beyond lower NIR-III

5. Third-Order Nonlinear Mechanisms for NIR-III Pulse Generation

5.1. Self-phase modulation (SPM)

SPM arises directly from the intensity-dependent refractive index. As a pulse propagates through a Kerr medium, its instantaneous phase becomes:

$$\phi(t, z) = \phi_0(t, z) + \gamma L_{\text{eff}} |A(t)|^2, \quad (5)$$

where ϕ_0 is the linear phase. The corresponding instantaneous frequency is:

$$\omega_{\text{inst}}(t) = -\frac{d\phi}{dt}. \quad (6)$$

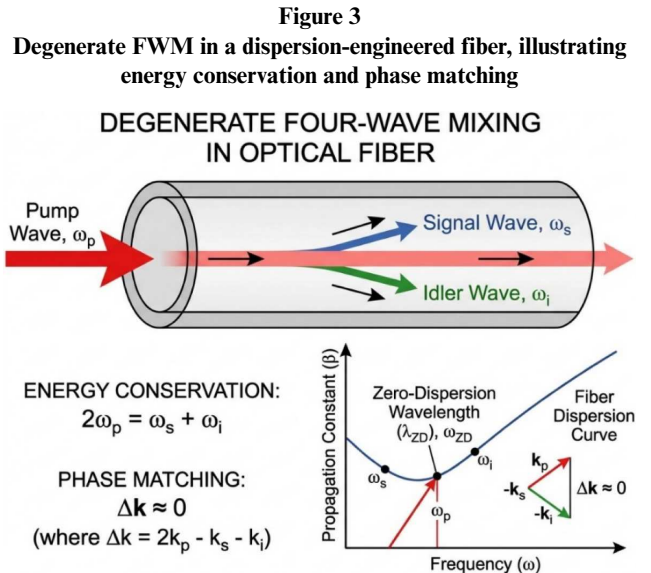
Because the intensity $|A(t)|^2$ varies in time, the leading and trailing edges acquire different frequency shifts, producing spectral broadening. In NIR-III systems, SPM is useful for broadening narrow seed pulses from Er-, Bi-, or Tm-based fiber lasers before compression or filtering. Its main advantages are simplicity, all-fiber compatibility, and preservation of relatively good coherence when operated below noise-dominated regimes. However, SPM alone mainly broadens the spectrum around the pump and does not strongly shift the center wavelength. Therefore, it is most effective as a bandwidth-enhancement stage rather than as a complete solution for wide NIR-III tunability [19, 20].

5.2. Four-wave mixing (FWM)

FWM is another key third-order nonlinear process in optical fibers, arising from the same Kerr nonlinearity that produces SPM and cross-phase modulation. In FWM, four optical waves at different angular frequencies ω_j interact through the $\chi^{(3)}$ medium's response, enabling energy transfer from strong pump waves to weaker signal and idler components at new frequencies. As a

result, FWM can be used for parametric wavelength conversion and amplification and is widely exploited in fiber-optical parametric amplifiers and fiber-optical parametric oscillators designed to generate tunable pulses in the NIR-III band [28]. The basic principle of degenerate FWM and its phase-matching condition are shown schematically in Figure 3 [29]. Two pump photons generate signal and idler photons according to energy conservation, while efficient conversion requires phase matching. In the NIR-III window, the fiber zero-dispersion wavelength and pump detuning strongly determine whether an idler can be generated in the desired 1550–1870 nm range.

In the simplest case of degenerate FWM, two of the four interacting frequencies are identical, $\omega_1 = \omega_2$, and act as a strong pump. A nearby frequency component ω_3 (the signal) is amplified



at the expense of the pump, while a new idler component appears at ω_4 . Conservation of energy imposes the familiar relation:

$$\omega_4 = 2\omega_1 - \omega_3, \quad (7)$$

so that for each photon added to the signal, two pump photons are depleted and one photon is generated at the idler frequency. Beyond energy conservation, phase matching must also be satisfied to accumulate FWM efficiently along the fiber. The total wave-vector mismatch is written as:

$$\Delta k = \Delta k_M + \Delta k_W + \Delta k_{NL} = 0, \quad (8)$$

where Δk_M and Δk_W are the contributions from material and waveguide dispersion, respectively, and Δk_{NL} arises from the nonlinear phase shift proportional to the pump power. For standard SMFs, the waveguide term is often negligible so that Δk_M is dominated by the second- and higher-order dispersion parameters $\beta_2, \beta_4, \dots$ at the pump frequency. Expanding the propagation constants in a Taylor series and introducing the frequency detuning $\Omega_s = \omega_1 - \omega_3 = \omega_4 - \omega_1$, the material contribution can be approximated as:

$$\Delta k_M \approx \Omega_s^2 \beta_2 + \frac{1}{12} \Omega_s^4 \beta_4, \quad (9)$$

illustrating that phase matching depends sensitively on both the pump wavelength relative to the zero-dispersion wavelength and the dispersion profile of the fiber.

FWM is attractive when narrowband tunability, spectral brightness, and parametric amplification are needed. It is especially useful in fiber optical parametric amplifiers and oscillators. Its limitations are phase-matching sensitivity, environmental drift, dispersion fluctuations, and relatively complex fiber design. Compared with SC generation, FWM can produce cleaner discrete wavelengths, but it generally offers less continuous spectral coverage unless the pump or cavity is tunable [23].

Fiber optical parametric amplifiers and oscillators are important practical implementations of FWM because they convert a strong pump into tunable signal and idler waves through the third-order susceptibility of the fiber. Compared with

Raman-based red-shifting, FWM is not limited to a fixed vibrational frequency shift. Instead, the generated wavelengths are determined by energy conservation and phase matching, which can be adjusted through pump wavelength, fiber dispersion, and nonlinear phase shift. This makes FWM attractive for tunable spectroscopy and wavelength-selective NIR-III generation, especially when narrowband output or parametric gain is required [42–44].

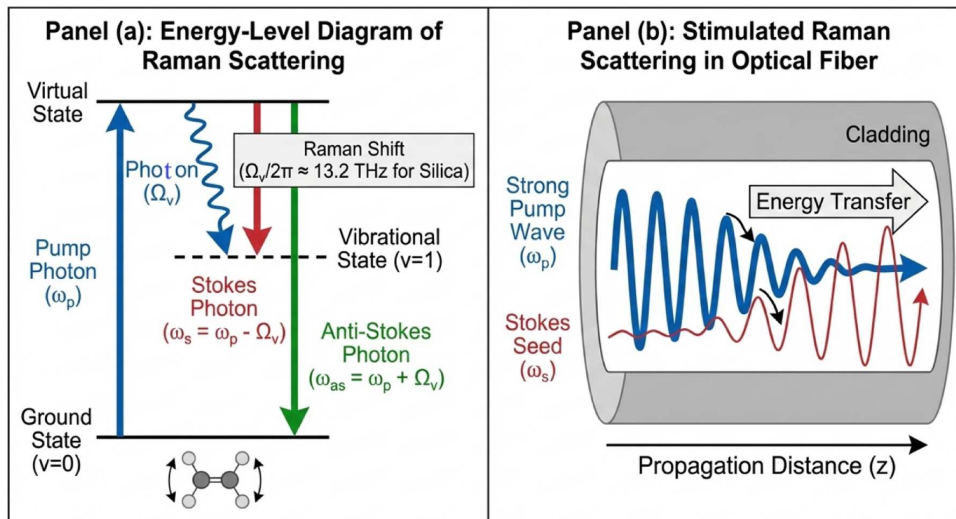
The main limitation is that high conversion efficiency requires careful control of the phase mismatch. Small variations in the zero-dispersion wavelength, pump detuning, temperature, strain, or fiber geometry can change the signal-idler gain spectrum. This sensitivity is a major reason why highly nonlinear fibers, dispersion-shifted fibers, microstructured fibers, and integrated waveguides have been explored for parametric wavelength conversion [45, 46]. In the NIR-III region, FWM is therefore best understood as a precision wavelength-conversion mechanism: it can provide clean and tunable spectral output but usually requires more careful dispersion design than SPM or simple Raman shifting.

5.3. Stimulated Raman scattering (SRS)

SRS is an inelastic scattering process in which part of the optical field's energy is transferred to the medium's vibrational modes. In contrast to the Kerr effect, where the nonlinear polarization does not exchange energy with the lattice, SRS explicitly involves excitation of molecular vibrations [2]. It thus redistributes energy between different frequency components of the light field. In a silica fiber, the pump at angular frequency ω_p interacts with vibrational modes at frequency ω_v to generate a lower-frequency Stokes wave at $\omega_s = \omega_p - \omega_v$ and a higher-frequency anti-Stokes wave at $\omega_{as} = \omega_p + \omega_v$. Because the anti-Stokes process requires the medium to be initially in an excited vibrational state, its probability is much lower, and in practice, the Stokes component dominates the energy transfer. The Raman gain becomes significant only when the pump power exceeds a characteristic Raman threshold, beyond which the Stokes wave grows exponentially along the fiber [3]. The physical origin of Raman scattering and the difference between spontaneous and stimulated Raman processes are illustrated schematically in Figure 4 [47, 48].

Figure 4

- (a) Energy-level diagram illustrating spontaneous Raman scattering, showing Stokes and anti-Stokes frequency components, and (b) stimulated Raman scattering (SRS) in optical fibers, where above-threshold pump power leads to exponential growth of the Stokes wave



For fused-silica fibers pumped in the telecom band, the main Raman shift is about 13.2 THz, which corresponds to a wavelength shift of roughly 113 nm for a 1550 nm pump. This means that even a single Stokes step can push light from 1.55 μm into the 1.6–1.7 μm region, and cascaded SRS (where the first Stokes wave acts as the pump for the second Stokes, and so on) can reach much deeper into the infrared (see Figure 5(a)). In this way, SRS provides a natural route for red-shifting fiber-laser emission into the NIR-III band, even when the rare-earth gain is centered at shorter wavelengths [40].

The historical development of Raman fiber sources is important because it shows why SRS remains relevant even in the presence of mature rare-earth fiber lasers. Raman oscillation in glass optical waveguides demonstrated that the transmission fiber itself could act as a nonlinear gain medium when the pump intensity and interaction length were sufficiently large [26]. Unlike rare-earth gain, which is tied to dopant energy levels, Raman gain is available over a broad range of pump wavelengths because the Stokes frequency is determined by the vibrational response of the host medium. This makes Raman conversion especially valuable when the desired output wavelength lies outside the efficient gain band of Er-, Tm-, Ho-, or Bi-doped fibers.

For ultrashort pulses, SRS must be considered together with dispersion and Kerr nonlinearity. The Raman response can transfer energy from shorter to longer wavelengths, while SPM and dispersion simultaneously reshape the pulse spectrum and temporal profile. In some operating regimes, this interaction can be useful because it produces red-shifted femtosecond or picosecond pulses in the NIR-III band. In other regimes, it can lead to excess noise, spectral instability, or pulse breakup. Therefore, Raman-based NIR-III sources require careful balancing of pump power, fiber length, dispersion, cavity feedback, and nonlinear threshold [28, 37].

One widely used strategy for NIR-III is to form a Raman fiber laser by combining a long silica fiber resonator with an external pump laser or with an active doped-fiber cavity. In such systems, the fiber itself provides Raman gain, while fiber Bragg gratings (FBGs) or random distributed feedback define the lasing wavelength [2]. Galiakhmetova describes, for example, a 1699 nm thulium-doped fiber (TDF) laser whose efficiency is limited when only TDF gain is used: a 2.7 m TDF pumped at 1565 nm and a 4 km SMF produce continuous-wave output with maximum power of about 0.33 W and efficiency of only 1.5% due to

SMF losses and the small emission cross-section of Tm at that wavelength [1]. By adding Raman gain—using an Er/Yb-doped fiber (EYDF) pumped at 976 nm to generate a strong 1565 nm Raman pump for the long SMF—the same cavity can operate with hybrid gain, significantly lowering the threshold and increasing the output power around 1.7 μm . This illustrates how SRS can complement rare-earth gain to overcome efficiency limitations in the NIR-III window [1–28].

Another important class of SRS-based NIR-III sources uses gas-filled HC-PCFs. Filling the empty core with hydrogen provides narrow, high-gain Raman lines so that even relatively modest pump pulses can be converted into efficient Stokes waves near 1.7 μm .

In the context of ultrashort pulse generation, SRS can be combined with mode-locked pumps to produce tunable picosecond or femtosecond pulses in NIR-III. For instance, Raman fiber lasers pumped by 1.6 μm dissipative soliton pulses have been demonstrated with tunable output between about 1.70 and 1.73 μm , showing that SRS can preserve short pulse durations while shifting the spectrum into the desired band, as illustrated in Figure 5(b). However, in this regime, SRS also interacts with other nonlinear effects—such as SPM and soliton dynamics—making the temporal and spectral profiles more complex and sometimes leading to noise-like pulse formation.

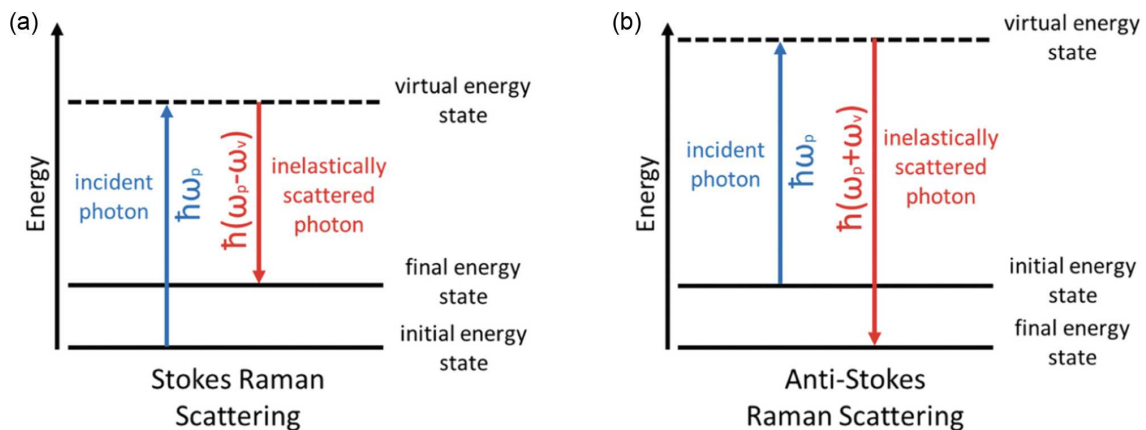
Overall, SRS offers a powerful and flexible mechanism to red-shift the emission of fiber lasers beyond the limits of rare-earth gain, making it particularly attractive for accessing the 1.6–1.8 μm region. Its main advantages are the ability to use standard silica fibers or gas-filled HC-PCFs as the gain medium and to generate wavelengths that are difficult to reach otherwise. On the other hand, efficient SRS typically requires high pump powers and long effective interaction lengths (kilometers of silica fiber or meter-scale HC-PCF cells), which can increase system complexity and footprint. For femtosecond sources, careful management of dispersion, nonlinearity, and cavity design is required to maintain clean pulse shapes and stable operation [1].

5.4. Soliton self-frequency shift (SSFS)

SSFS is a Raman-induced nonlinear effect that occurs when ultrashort soliton pulses propagate in the anomalous-dispersion regime of an optical fiber. Physically, it can be viewed as a special case of intrapulse Raman scattering, in which energy is transferred

Figure 5

Spontaneous Raman scattering. (a) Stokes scattering produces a lower-frequency photon and is commonly used for NIR-III red-shifting, and (b) anti-Stokes scattering produces a higher-frequency photon and is weaker because it requires initial vibrational excitation.



from the high-frequency (blue) side of the soliton spectrum to the low-frequency (red) side. This asymmetric energy flow causes a continuous red-shift of the soliton's central frequency as it travels along the fiber. Because solitons maintain a balance between dispersion and Kerr nonlinearity, the pulse can preserve a localized shape while its carrier wavelength drifts toward longer wavelengths. Figure 6 illustrates how an ultrashort soliton maintains its temporal localization while its spectrum continuously shifts toward longer wavelengths due to intrapulse Raman scattering [49, 50].

The theoretical foundation of SSFS comes from the fact that the Raman response acts as a perturbation to the ideal soliton solution. In the absence of perturbations, a fundamental soliton in the anomalous-dispersion regime maintains its temporal and spectral shape because dispersion and Kerr nonlinearity are balanced. When the delayed Raman response is included, however, the soliton continuously transfers energy from the blue side of its spectrum to the red side. The result is a gradual shift of the soliton carrier frequency toward longer wavelengths while the pulse remains temporally localized [22–24]. This behavior makes SSFS particularly attractive for NIR-III generation because a mature femtosecond Er-doped source near 1.55 μm can be used as the starting point and shifted toward 1.7–1.9 μm through nonlinear propagation.

In practice, the achievable red-shift depends on soliton order, pulse energy, fiber dispersion, effective mode area, and propagation length. Standard SMFs can provide useful SSFS but often require long fiber lengths and are limited in pulse-energy scaling because of their relatively high nonlinear coefficient. LMA fibers and photonic-crystal fibers reduce this limitation by supporting higher pulse energies and allowing more flexible dispersion design. These features explain why SSFS has become one of the most important approaches for generating tunable femtosecond pulses in the NIR-III band, especially for nonlinear microscopy and deep-tissue imaging applications [51].

In the framework of the generalized NLSE, SSFS arises from the delayed Raman response term, which introduces a time derivative of the intensity into the nonlinear polarization. This term causes an effective deceleration of the soliton in the time

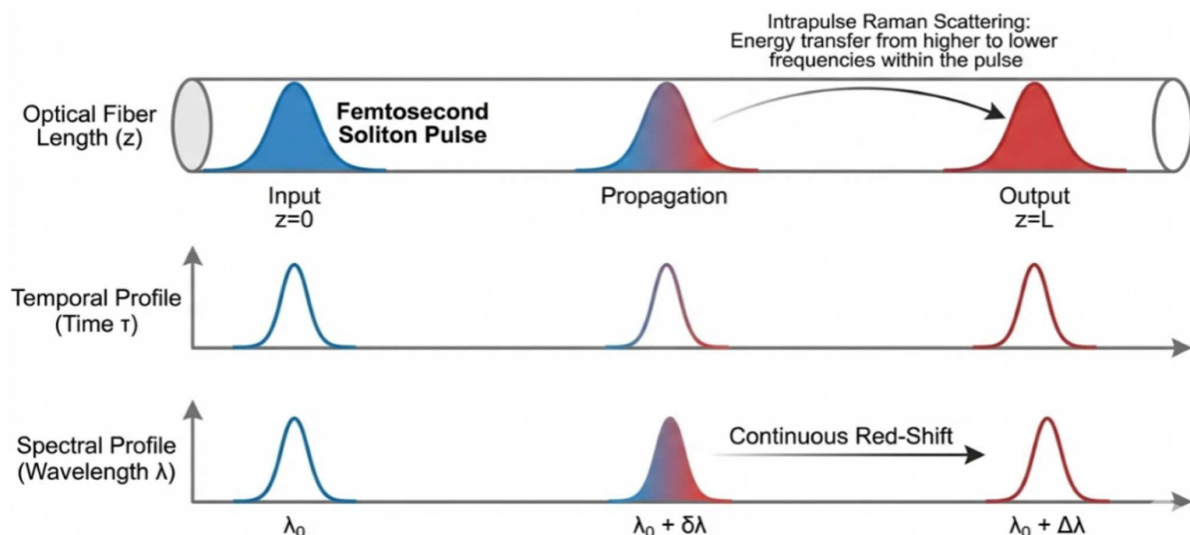
frame moving with the group velocity, and a corresponding red-shift of the carrier frequency. The magnitude of the shift increases with propagation distance, peak power, and pulse duration (shorter pulses with higher peak power experience stronger shifts). In standard silica SMFs, noticeable spectral shifts typically require hundreds of meters of fiber, especially when starting from telecom-band solitons around 1.55 μm . Under suitable conditions, this effect can move the operating wavelength of an Er-doped fiber laser (EDFL) into the 1600–1900 nm range, effectively migrating a telecom-band source into the NIR-III window without changing the gain medium. The system combines an all-Polarization-Maintaining (PM) Nonlinear Amplifying Loop Mirror (NALM)-based Er-doped oscillator, pumped at 976 nm, with a long PM fiber “SSFS module.” The oscillator produces ~ 180 fs pulses at 1560 nm with an average power of 53 mW [1]. When these pulses propagate through 460 m of PM fiber, intrapulse Raman scattering induces SSFS, shifting the spectrum to around 1700 nm and yielding ~ 384 fs pulses with 35 mW average power. This design illustrates the key idea: start with a robust Er-based femtosecond source near 1.55 μm , then use SSFS in standard (but long) telecom fiber to reach the 1.7 μm band relevant for the NIR-III biological window [52, 53].

To overcome the energy and length limitations of standard SMFs, many groups have turned to LMA fibers, which reduce the nonlinear coefficient γ while still supporting soliton dynamics at higher pulse energies. A widely tunable all-fiber EDFL architecture based on SSFS in very-large-mode-area (VLMA) Er-doped PM fibers has been demonstrated in several laboratory implementations. Systems using ~ 50 μm -core VLMA fibers pumped by 1480 nm Raman lasers have achieved soliton red-shifts extending approximately from 1620 nm to ~ 1900 –2000 nm, with sub-120 fs pulse durations and watt-level average powers. These results show that reducing the nonlinear coefficient γ through VLMA fiber design enables large wavelength tunability and high power scaling in the NIR-III band.

A complementary approach uses large-mode-area photonic crystal fibers (LMA PCFs) as the SSFS medium. Stoliarov et al. [54] developed an all-PM fiber mode-locked oscillator with a

Figure 6

Conceptual illustration of SSFS. An ultrashort soliton remains temporally localized while its spectrum shifts toward longer wavelengths because of intrapulse Raman scattering. The mechanism is especially useful for shifting telecom-band femtosecond pulses into the NIR-III window



NALM and an Er-doped preamplifier, followed by a chirped-pulse amplification stage based on EYDF. After stretching to 40.6 ps in an FBG and amplification to 1.2 W, the pulses are compressed to 660 fs using diffraction gratings and then launched into a 1 m LMA PCF with anomalous dispersion [54]. Inside the PCF, high-order solitons form and are perturbed by higher-order dispersion, leading to soliton fission into multiple fundamental solitons of different widths [18]. Intrapulse Raman scattering then causes each fundamental soliton to undergo SSFS, with the highest-order soliton experiencing the largest red-shift. At a pump power of 221 mW, the output is centered at 1625 nm with 165 fs pulse duration and 55 mW average power; increasing the pump power to 321 mW shifts the soliton center to 1700 nm and compresses the pulse to 91 fs while increasing the average power to 107 mW. This example highlights how pump power and fiber length/dispersion control the final wavelength and pulse duration [1].

Beyond silica solid-core fibers, SSFS has also been exploited in antiresonant and other specialty fibers designed for biomedical imaging. High-energy solitons shifted to 1.6–1.8 μm in LMA antiresonant fibers have been used to drive three-photon microscopy, taking advantage of the NIR-III biological window to reach deep cortical structures with reduced scattering. Similarly, high-power SSFS sources with flattened spectra between 1.6 and 1.78 μm have been developed for broadband excitation in nonlinear imaging. These works show that SSFS-based fiber lasers can provide high spectral power density and excellent beam quality, both of which are critical for advanced biophotonics.

In summary, SSFS offers an elegant and highly effective way to shift femtosecond soliton pulses from the telecom band into the NIR-III region, enabling tunable ultrafast sources between roughly 1.6 and 2.0 μm . Its key strengths are (i) continuous wavelength tunability controlled by pulse energy, fiber length, and dispersion, (ii) the ability to maintain short pulse durations (often <200 fs), and (iii) compatibility with all-fiber architectures based on Er-doped master oscillators. On the other hand, SSFS in standard SMF is constrained by relatively high nonlinearity, which limits the achievable pulse energy to below ~ 1 nJ and can induce excessive nonlinear distortions if the peak power is too large. The Galiakhmetova review [1] notes that “the relatively high nonlinearity of the SMF limits the pulse energy to less than 1 nJ” and suggests that using fibers with a lower nonlinear coefficient γ (e.g., VLMA fibers or LMA PCFs) significantly improves performance in the NIR-III range. Moreover, precise management of dispersion and higher-order effects is required to control soliton fission and to avoid unstable or noise-like outputs. Despite these challenges, SSFS-based designs currently represent some of the most powerful and versatile ultrafast sources for the NIR-III band, especially in applications that demand high brightness, deep tissue penetration, and flexible wavelength tuning.

5.5. Supercontinuum (SC) generation

SC generation is the broadband limit of nonlinear pulse propagation, where a narrowband pump evolves into a spectrum spanning hundreds of nanometers or more. It is not a single physical effect but the combined result of SPM, FWM, modulation instability, SRS, SSFS, soliton fission, and dispersive-wave emission. The outcome depends strongly on pump duration, peak power, fiber dispersion, nonlinear coefficient, and noise seeding.

The development of SC sources began with early observations of extreme spectral broadening in nonlinear media and later became especially powerful after the introduction of photonic-crystal

fibers [55, 56]. Photonic-crystal fibers enabled strong confinement, small effective mode area, and dispersion profiles that could be engineered near the pump wavelength. These features made it possible to generate broadband spectra using compact femtosecond or picosecond pump sources. For NIR-III applications, the same design principles are used to extend spectral energy into the 1.6–1.9 μm range and beyond.

A major practical issue in SC generation is coherence. When SC is generated in an anomalous-dispersion regime dominated by modulation instability and soliton fission, small pump fluctuations can be amplified into large shot-to-shot spectral variations. This leads to relative-intensity noise and reduced coherence, which can limit the usefulness of SC sources for OCT, spectroscopy, and quantitative biomedical imaging [11–14]. All-normal-dispersion fibers can improve coherence by promoting smoother SPM-dominated broadening, although this approach may reduce the achievable bandwidth or spectral power density [14]. Therefore, SC generation offers the broadest NIR-III coverage, but it also requires the most careful treatment of noise, coherence, and dispersion management.

For NIR-III applications, SC generation is valuable because a single source can cover multiple wavelengths across the NIR-II and NIR-III regions. This is useful for broadband OCT, multi-spectral photoacoustic imaging, spectroscopy, and nonlinear microscopy. However, SC sources can suffer from relative-intensity noise and reduced coherence, especially when generated in anomalous-dispersion regimes dominated by modulation instability and soliton fission. All-normal-dispersion fibers can improve coherence but may reduce bandwidth or conversion efficiency. Thus, SC generation is powerful but requires careful design when stability and low noise are critical [40, 41].

6. Quantitative and Critical Comparison of Nonlinear NIR-III Mechanisms

The choice of nonlinear mechanism depends on the required output wavelength, bandwidth, pulse duration, spectral power density, noise tolerance, and system complexity. Table 2 summarizes the main practical trade-offs. The values are representative ranges drawn from reported NIR-III fiber-source demonstrations and are intended to guide mechanism selection rather than define absolute limits.

The noise behavior of each nonlinear mechanism is closely connected to the physical process that generates the new wavelengths. In SPM-dominated broadening, the output can remain highly coherent because the spectral broadening is largely deterministic and follows the temporal intensity profile of the input pulse. In contrast, anomalous-dispersion SC generation can amplify quantum noise or technical pump fluctuations through modulation instability, producing strong shot-to-shot spectral variations [11–13]. In SSFS systems, the output wavelength is sensitive to pulse energy because a higher-energy soliton generally undergoes a larger Raman-induced red-shift. This means that input energy fluctuations can appear as wavelength jitter. In FWM systems, phase-matching drift can change both conversion efficiency and signal-idler wavelength, while Raman systems can show threshold sensitivity and mode competition depending on cavity design and gain distribution.

These noise pathways are especially important for NIR-III biomedical sources. In multiphoton microscopy, pulse-to-pulse energy stability affects excitation efficiency and image brightness. In OCT, spectral coherence and relative-intensity noise influence axial resolution and sensitivity. In photoacoustic imaging, pulse energy stability affects signal amplitude and quantitative

Table 2

Critical comparison of $\chi^{(3)}$ mechanisms for NIR-III fiber laser and amplifier design. The table emphasizes performance trade-offs rather than only the underlying physical mechanism

Mechanism	NIR-III wave-length behavior	Pulse-duration trend	Power/energy scalability	Coherence/noise trend	Complexity	Best use	Main limitation
SPM [19, 20]	Pump-centered broadening, typically tens of nm	fs-ps; often compressible	Low to moderate; limited by nonlinear phase distortion	High when deterministic	Low	Simple spectral broadening and seed preparation	Limited center-wavelength shift
FWM [29]	Discrete/-tunable signal-idler bands; >250 nm possible with engineered fibers	ps-fs depending on pump/-cavity	Medium; depends on phase matching and Highly Nonlinear Fiber (HNLF)/ Dispersion-Shifted Fiber (DSF) design	High if phase matched and stable	Medium	Tunable spectroscopy and parametric amplification	Sensitive to dispersion and environmental drift
SRS [52, 53]	Red-shifted Stokes bands; cascaded shifts can reach deeper IR	cw-ns-ps-fs depending on pump	Medium to high in Raman cavities or gas-filled HC-PCF	Moderate to high; depends on pump noise and cavity	Medium	Efficient 1.6–1.8 μm conversion	Threshold, long fibers, gas cells, or specialty fibers
SSFS [50]	Continuous red-shift, often ~1.6–2.0 μm	Often <200 fs in optimized systems	Medium to high with LMA/PCF; limited in SMF	High if soliton dynamics controlled	Low to medium	Ultrafast microscopy and clean tunable femtosecond NIR-III pulses	Dispersion sensitivity and soliton fission control
SC [49]	Ultra-broad; hundreds of nm to octave-scale	Broadband pulses; temporal structure can be complex	High average power possible; spectral density spread across bandwidth	Variable; can be noisy in anomalous dispersion	High	Broadband OCT, spectroscopy, multi-modal imaging	Noise, coherence degradation, and specialty-fiber complexity

interpretation. As a result, source design should report not only wavelength range and average power but also pulse duration, pulse energy, repetition rate, relative-intensity noise, spectral stability, and long-term operating stability. Without these parameters, direct comparison between SPM-, FWM-, SRS-, SSFS-, and SC-based NIR-III sources remains incomplete.

Table 3 provides a more application-oriented comparison of representative source-design directions. It highlights that the best nonlinear pathway changes depending on whether the priority is broadband coverage, wavelength-selective power, ultrashort pulse duration, low noise, or implementation simplicity

6.1. Noise, coherence, and stability

Noise is a central practical limitation in NIR-III nonlinear sources. In SC generation, modulation instability and soliton fission can amplify small pump fluctuations, leading to spectral fluctuations and reduced coherence. In FWM systems, phase-matching drift caused by temperature, strain, or dispersion variation can change conversion efficiency and output wavelength. In SSFS systems, input pulse-energy fluctuations can directly translate into wavelength jitter because the red-shift depends on soliton energy. SRS systems can exhibit mode

Table 3
Application-driven selection of nonlinear NIR-III fiber-source architectures

Application	Dominant source requirement	Preferred nonlinear route	Reason	Key challenge
Biomedical multiphoton microscopy [39, 50]	1.6–1.8 μm fs pulses, high peak power, low noise	SSFS; SRS/SSFS hybrids	Clean femtosecond pulses and tunable red-shift from Er-based seeds	Requires dispersion and soliton-fission management
Optical coherence tomography [49]	Broad bandwidth, low noise, stable spectrum	SC; all-normal-dispersion SC	Broad axial-resolution-supporting bandwidth	Coherence and relative-intensity noise must be controlled
Gas sensing and spectroscopy [53]	Narrowband tunability and spectral brightness	FWM; SRS	Selectable wavelengths and high spectral density	Phase matching or Raman-line selection constrains range
Photoacoustic imaging [52]	High pulse energy at selected NIR-III wavelengths	SRS; Tm/Bi gain plus nonlinear shifting	Good spectral power density near absorption bands	Pulse duration and repetition rate may be less flexible
Compact seed broadening [20]	Simple all-fiber bandwidth increase	SPM	Low-complexity and compatible with telecom components	Usually insufficient for wide NIR-III tuning alone

competition, threshold sensitivity, or cavity instability when the Raman gain is distributed over long lengths [52, 53].

6.2. Dispersion management and fiber architecture

Dispersion management is the practical bridge between nonlinear physics and useful NIR-III source design. For FWM, dispersion determines phase matching. For SSFS, it determines soliton order, fission length, and red-shift dynamics. For SC generation, it governs the balance between coherent SPM-dominated broadening and noise-sensitive modulation-instability dynamics. LMA fibers reduce the nonlinear coefficient and support higher energy. Hollow-core and gas-filled fibers reduce material overlap or introduce strong molecular Raman gain. Photonic-crystal fibers allow tailored dispersion but can add splicing and handling complexity [31].

6.3. No universal best mechanism

There is no single best nonlinear mechanism for the NIR-III window. SPM is simple and coherent but limited in wavelength shift. FWM is spectrally clean and tunable but phase-matching sensitive. SRS is efficient for red-shifting but can require long fibers, gas cells, or high pump power. SSFS provides elegant continuous femtosecond tunability but requires careful soliton control. SC generation offers the broadest coverage but often introduces the strongest noise and coherence challenges. The appropriate choice must therefore be made from the target application backward, not from the nonlinear mechanism forward [52, 53].

7. Conclusions and Outlook

This review has examined how third-order nonlinear effects in optical fibers enable fiber laser and amplifier operation in the NIR-III spectral window of approximately 1550–1870 nm. Direct gain media remain essential, but they do not yet provide wide, efficient, high-energy, ultrafast coverage across the entire region. Nonlinear wavelength conversion, therefore, provides a necessary design pathway for converting mature seed sources into tunable NIR-III outputs.

The revised emphasis of this paper is that NIR-III nonlinear source design is governed by practical trade-offs. SPM provides simple, coherent broadening but little center-wavelength shift. FWM offers parametric tunability and spectral brightness but requires precise phase matching. SRS provides efficient Raman red-shifting into the lower and middle NIR-III region. SSFS enables clean, continuously tunable femtosecond pulses from telecom-band seeds. SC generation offers broad spectral coverage but requires careful noise and coherence management.

Future progress will likely come from three directions. First, LMA, antiresonant, and hollow-core fibers will improve pulse-energy scaling while reducing unwanted nonlinear distortion. Second, dispersion-engineered and soft-glass fibers will allow more efficient phase matching and broader spectral extension. Third, hybrid architectures that combine rare-earth gain, Raman gain, soliton shifting, and parametric conversion may provide more stable and application-specific NIR-III sources. Better feedback control, lower-noise master oscillators, and machine-learning-assisted optimization may also improve the stability of complex nonlinear dynamics such as SC generation and high-order soliton fission.

A further direction for the field is the integration of nonlinear source design with the specific needs of biomedical and spectroscopic applications. For example, deep-tissue multiphoton microscopy benefits from femtosecond pulses near 1.7 μm with high peak power and low noise, making SSFS and Raman-assisted SSFS particularly attractive. OCT and broadband spectroscopy require wide and stable spectra, which motivates coherent SC generation in carefully dispersion-engineered fibers. Narrowband spectroscopy and wavelength-selective sensing may benefit more from FWM or Raman systems because these approaches can provide higher spectral power density at selected wavelengths. Thus, future NIR-III fiber sources should be optimized from the application backward rather than selected only according to the nonlinear mechanism.

Progress will also depend on more standardized reporting. Many published demonstrations report output wavelength and average power, but fewer provide complete information on pulse energy, pulse duration, spectral power density, noise, coherence, beam quality, conversion efficiency, and long-term

stability. These missing details make it difficult to compare different NIR-III source architectures fairly. Future work should therefore combine improved fiber design with clearer performance reporting so that source selection can be guided by measurable application requirements rather than by wavelength coverage alone.

Overall, χ^3 -based fiber nonlinearities have transformed NIR-III source development by allowing conventional Er-, Yb-, Tm-, Ho-, and Bi-based systems to reach wavelengths and pulse formats that direct gain alone cannot easily provide. With continued advances in fiber design, dispersion engineering, and system integration, NIR-III nonlinear fiber lasers are expected to become more efficient, compact, stable, and useful for biomedical, spectroscopic, and photonic applications.

Recommendations

Future work should focus on application-driven source design rather than mechanism selection alone. For biomedical imaging, emphasis should be placed on low-noise femtosecond SSFS and SRS/SSFS hybrid systems. For spectroscopy, phase-stable FWM and Raman systems should be optimized for narrowband brightness and tunability. For broadband imaging and sensing, SC systems should prioritize coherence preservation and relative-intensity-noise reduction. Across all platforms, improved reporting of pump wavelength, output range, pulse duration, average power, pulse energy, efficiency, noise, and fiber architecture would make future reviews and cross-comparisons more reliable.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

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