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A Comprehensive Review of Nonlinear Optics: Fundamentals, Materials, Devices, and Applications

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Abstract: Nonlinear optics has evolved from bulk, high-field laboratory experiments into a practical basis for integrated photonic devices. This review connects the underlying second-order (χ^2) and third-order (χ^3) responses with the engineering constraints that govern chip-scale performance. It compares thin-film lithium niobate, silicon nitride, III–V semiconductors, chalcogenide glasses, epsilon-near-zero (ENZ) oxides, and nonlinear metasurfaces using a system-level framework rather than the nonlinear coefficient alone. Across these platforms, propagation loss, phase matching, dispersion, thermal drift, fabrication tolerance, coupling, and packaging often determine usable conversion efficiency more strongly than an isolated material parameter. Thin-film lithium niobate is especially effective for χ^2 conversion and electro-optic control; silicon nitride supports low-loss, high-Q Kerr combs; III–V materials provide strong confinement and compact interaction lengths; and ENZ structures and metasurfaces exploit local-field enhancement in ultrathin geometries. The review also evaluates measurement and reporting practices, fabrication-aware inverse design, programmable nonlinear interactions, and reliability requirements. No platform is universally superior: the appropriate choice depends on application-specific demands for efficiency, bandwidth, noise, tunability, footprint, and manufacturability. Future progress will require consistent benchmarking, uncertainty-aware optimization, wafer-scale process control, and packaging strategies that preserve laboratory performance in deployable systems.

Keywords: integrated nonlinear photonics, thin-film lithium niobate, Kerr microcombs, nonlinear metasurfaces, inverse design

1. Introduction

At low optical intensity, the response of most optical materials can be treated as almost linear: the induced polarization follows the applied electric field in a nearly proportional way. This simple picture changes when the field becomes strong. Higher-order polarization terms begin to contribute, and the material can then mix frequencies or alter the phase of the propagating light. This is the basis of nonlinear optics. It explains familiar processes such as second-harmonic generation (SHG), sum- and difference-frequency generation (SFG/DFG), spontaneous parametric down-conversion (SPDC), optical parametric amplification and oscillation (OPA/OPO), four-wave mixing (FWM), self-phase modulation (SPM), and supercontinuum generation (SCG) [1, 2].

Historically, most of these phenomena were observed in bulk nonlinear crystals driven by high-energy pulsed lasers. The optical layouts were usually free-space arrangements with careful alignment and stable laboratory conditions. They were scientifically important, but their size and sensitivity made them difficult to translate into compact photonic hardware. Integrated photonics changed this picture. A waveguide can confine light into a small mode area, so the local intensity becomes high even when the input power is not large. When this confinement is combined with engineered dispersion and resonant enhancement in microresonators, nonlinear effects can appear at pump powers that are far below those normally required in bulk free-space systems [3–5].

This movement from bulk optics to integrated platforms also changed the design problem. Choosing a material with a large nonlinear coefficient is only the starting point. A real nonlinear device must keep the interacting waves phase matched, avoid excessive propagation loss, tolerate temperature changes, couple efficiently to fibers or other chips, and survive the small geometry variations that occur during fabrication. In a narrow waveguide, a few nanometers of width or thickness error can shift the dispersion enough to alter the nonlinear response. For that reason, integrated nonlinear photonics is best judged at the device and system level, not only at the level of intrinsic material nonlinearity.

This review therefore takes a system-oriented view of integrated nonlinear photonics. It discusses the main material platforms in terms of how they behave in actual devices, where loss, phase control, thermal behavior, fabrication repeatability, and packaging are as important as the nonlinear coefficient. The review also includes inverse design, programmable nonlinear optics, and measurement standards because these topics now determine whether a laboratory demonstration can become a reproducible and manufacturable photonic technology.

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Figure 1 outlines the transition from bulk demonstrations to programmable, fabrication-aware integrated systems.

2. Condensed Fundamentals of Nonlinear Optics

2.1. Polarization expansion and nonlinear orders

For a weak optical field, the induced polarization P can be described by the first-order response of the medium. Once the field strength is high enough, the linear term no longer gives the full response and higher-order terms must be retained. The polarization is usually written as:

$$P(t) = \varepsilon_0 \left[\chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \dots\right] \quad (1)$$

where $\chi^{(1)}$ is the linear susceptibility, while $\chi^{(2)}$ and $\chi^{(3)}$ represent the second- and third-order nonlinear responses, respectively [1, 2]. This expansion is useful because it connects the mathematical form of the material response to observable processes. The $\chi^{(2)}$ term allows frequency conversion such as SHG and SFG/DFG, whereas $\chi^{(3)}$ is responsible for effects such as Kerr phase shifts, FWM, third-harmonic generation (THG), and SCG.

The $\chi^{(2)}$ response is symmetry dependent. It vanishes in centrosymmetric media and is therefore observed in non-centrosymmetric materials such as lithium niobate, GaAs, and GaP. The $\chi^{(3)}$ response is less restricted by symmetry and can appear in a much wider set of materials. In a waveguide, however, the coefficient itself is not enough to predict the result. Mode overlap, effective length, phase mismatch, propagation loss, and the actual intensity inside the guided mode all contribute. This is why a platform with a moderate nonlinear coefficient can still perform well when the optical mode is tightly confined and the loss is low.

The expansion above should also be understood as a perturbative description. In other words, the nonlinear terms are treated as corrections to the dominant linear response. This assumption is valid for most integrated photonic devices operated at typical pump powers. It should not be confused with strong-field regimes, such as high-harmonic generation (HHG) in solids, where the electron dynamics and band structure must be treated differently. Table 1 summarizes the principal nonlinear processes and their main design implications.

2.2. Figures of merit

Several quantities are commonly used to describe nonlinear photonic platforms, including the effective quadratic nonlinearity d_eff, Kerr nonlinear index n_2, nonlinear absorption coefficient β_TPA or higher-order absorption terms, propagation loss α, thermo-optic coefficient, damage threshold, effective mode area, Q factor, coupling efficiency, and dispersion. These quantities should not be read separately. A large d_eff or n_2 can be offset by scattering, two-photon absorption, thermal drift, poor coupling, or a narrow fabrication tolerance window. For integrated devices, the useful figure of merit is therefore a combined one: the platform must provide enough nonlinear strength while keeping loss, heating, and process sensitivity under control [3, 5–8].

Figure 1
Roadmap from bulk/free-space nonlinear optics toward programmable and fabrication-aware integrated nonlinear photonics

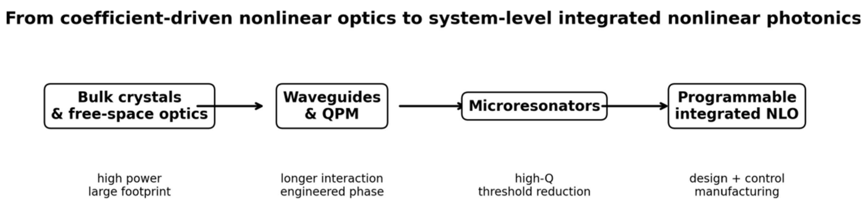


Table 1
Condensed classification of key nonlinear optical processes, with perturbative THG distinguished from non-perturbative HHG

Process	Order	Main interaction	Important design point
SHG	χ^2	$\omega + \omega \rightarrow 2\omega$	Needs phase matching and strong fundamental/second-harmonic mode overlap
SFG/DFG	χ^2	$\omega_1 \pm \omega_2 \rightarrow \omega_3$	Useful for wavelength translation, mid-IR generation, and quantum interfaces
SPDC	χ^2	$\omega p \rightarrow \omega s + \omega i$	Quantum-source quality depends on brightness, spectral purity, coupling, and stability
OPA/OPO	χ^2 or χ^3	Parametric gain/oscillation	Threshold depends on nonlinear gain, cavity loss, and phase matching
FWM	χ^3	$2\omega p \rightarrow \omega s + \omega i$	Requires dispersion control; central to Kerr combs and wavelength conversion
THG	χ^3	$\omega + \omega + \omega \rightarrow 3\omega$	Perturbative third-order process; not equivalent to strong-field HHG
HHG in solids	Non-perturbative	Strong-field electron dynamics	Distinct from perturbative THG; requires high fields and band-structure treatment
SCG	χ^3 plus dispersion	SPM, Raman, soliton dynamics	Broadband output requires anomalous/engineered dispersion and damage control

3. Material Platforms for Integrated Nonlinear Photonics

3.1. Thin-film lithium niobate and periodically poled lithium niobate

Lithium niobate remains a reference χ^2 material because it combines a relatively large d_{33} coefficient, about 25–27 pm/V, with a strong electro-optic response and a broad transparency window [4, 9, 10]. Thin-film lithium niobate (TFLN), commonly implemented as lithium niobate on insulator (LNOI), has made this long-known material much more relevant to integrated photonics. Compared with bulk periodically poled lithium niobate (PPLN), the thin-film form allows tighter confinement, shorter interaction lengths, and the combined use of quasi-phase matching (QPM) with waveguide dispersion engineering [9, 11–16]. Recent work in quantum photonics and electro-optics also shows why this platform is attractive: nonlinear generation, modulation, and active control can be placed on the same chip rather than treated as separate subsystems [11, 17].

3.2. Silicon nitride and silica-compatible platforms

Silicon nitride (SiN) has become one of the most reliable χ^3 platforms in integrated nonlinear photonics. Its importance does not come from having the largest Kerr coefficient but from the way several practical advantages meet in the same material system. SiN waveguides and resonators can be fabricated with very low propagation loss, show negligible two-photon absorption at telecom wavelengths, and allow accurate dispersion control through geometry. These features are important in Kerr-comb and broadband nonlinear devices, where the optical field must remain confined and stable over many cavity round trips [5, 18]. In high-Q SiN resonators, the long photon lifetime partly compensates for the moderate intrinsic nonlinearity, so useful nonlinear interaction can be achieved without relying on extremely large material coefficients. Recent progress in anneal-free and low-temperature SiN fabrication, with losses reaching the dB/m range, also shows a clear shift in the field: process compatibility, wafer-scale repeatability, and heterogeneous integration are now as important as the nonlinear response itself [19, 20].

3.3. III–V semiconductors: AlGaAs, GaP, and InGaP

III–V semiconductors represent a distinct class of nonlinear photonic platforms. Their main advantage is the high refractive index, which allows the optical mode to be tightly confined inside compact waveguide and resonator structures. This strong confinement increases the local field intensity and makes nonlinear interaction efficient over short device lengths. Many III–V materials also provide both χ^2 and χ^3 responses, giving them flexibility for frequency conversion, comb generation, and quantum-light applications.

Among these platforms, AlGaAs-on-insulator (AlGaAsOI) has attracted particular attention because it can support compact frequency-comb sources and high-Q resonators. Its performance becomes especially useful when the material composition is selected to suppress two-photon absorption at telecom wavelengths, allowing the nonlinear response to be used without excessive nonlinear loss [21]. Gallium phosphide on insulator (GaP-OI) and indium gallium phosphide (InGaP) are also important, but for a different reason. Their transparency range and nonlinear properties make them suitable for linking visible and telecom wavelengths, which is valuable in integrated quantum photonics, where photon generation, routing, and wavelength conversion may need to occur on the same chip [22–24].

The main limitation of III–V platforms is therefore not the absence of strong nonlinear physics. The more difficult part is technological. Wafer bonding quality, sidewall roughness after etching, thermal dissipation, and device-to-device repeatability still affect practical performance. As a result, III–V nonlinear photonics offers high efficiency and compact footprints, but wider adoption depends on improving fabrication uniformity and making the process more reliable at wafer scale.

3.4. Chalcogenide glasses

Chalcogenide glasses are valuable nonlinear materials because they offer a strong Kerr response and can remain transparent across a broad spectral range, including parts of the mid-infrared (IR). This gives them an advantage in applications where conventional silica-based platforms, and in some cases SiN, become less effective because of limited transparency or weaker nonlinear performance. For this reason, chalcogenide waveguides have attracted attention for SCG, mid-IR sensing, and nonlinear photonic circuits operating at longer wavelengths [25, 26].

Their performance, however, depends strongly on how the material is prepared and integrated. Film composition, deposition conditions, annealing, surface roughness, and photosensitivity can all influence optical loss and long-term stability. These factors are important because a high Kerr coefficient alone is not enough if the fabricated device suffers from instability or poor repeatability. Compatibility with standard silicon-photonic workflows is also a practical concern, especially when chalcogenide devices are intended to be combined with passive or active photonic components.

Recent studies on reconfigurable chalcogenide microresonators are therefore important. They show that the dispersion of the device can be modified after fabrication instead of being fixed completely by the initial geometry. This post-fabrication tunability gives the platform more flexibility: if the fabricated resonator does not exactly match the designed phase-matching condition, the nonlinear response may still be adjusted or recovered. In this sense, reconfigurable chalcogenide photonics offers not only high nonlinearity but also a practical route for improving device tolerance and usable performance [27].

3.5. ENZ materials and nonlinear metasurfaces

Epsilon-near-zero (ENZ) materials and nonlinear metasurfaces follow a different strategy from conventional waveguide platforms. Instead of relying mainly on long interaction lengths or high-Q confinement, they try to strengthen the local optical field itself. In transparent conducting oxides operated close to the ENZ condition, the real part of the permittivity approaches zero, which can produce strong-field enhancement inside or near the material. As a result, very large effective nonlinear responses can be observed even when the physical thickness of the active region is small [28–31].

Nonlinear metasurfaces use a related idea, but with more structural control. By arranging subwavelength resonators such as dielectric, plasmonic, III–V, or hybrid meta-atoms, these platforms can enhance second- or third-harmonic generation while also controlling the phase, polarization state, and emission direction of the generated light [32–35]. This makes them attractive for flat nonlinear optical components, compact harmonic sources, and beam-shaping elements that would be difficult to realize using bulk nonlinear crystals.

The main challenge is that strong local-field enhancement does not necessarily lead to high usable output efficiency. Part of the generated signal may remain trapped near the resonant structure, while absorption and heat accumulation can reduce practical conversion efficiency. In addition, the short interaction length and the difficulty of fabricating large-area metasurfaces with uniform optical response still limit system-level performance. Recent demonstrations of nonlinear dielectric metasurfaces in the terahertz range show that the concept is expanding beyond visible and near-IR photonics, but the same engineering issues—loss, heating, uniformity, and external extraction efficiency—still require careful attention [36].

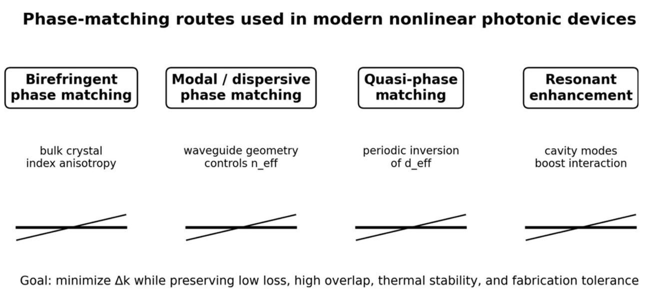
4. Phase Matching, Dispersion Engineering, and Fabrication Tolerance

Efficient nonlinear frequency conversion requires energy conservation and phase matching between the interacting waves. In a waveguide, the phase mismatch may be written, for example, as $\Delta k = k_3 - k_2 - k_1$ for sum-frequency generation, with analogous signed combinations for other nonlinear processes. In an integrated device, however, Δk is not controlled by material dispersion alone. It is also shifted by waveguide width, film thickness, etch depth, sidewall angle, temperature, resonator detuning, and, in periodically poled structures, the quality and duty cycle of the poling pattern. For this reason, phase matching in integrated nonlinear optics is best treated as a tolerance problem rather than as one ideal design point.

Several routes are used to control this mismatch. Birefringent phase matching remains important in bulk crystals but is less flexible for dense photonic circuits. Modal and dispersion-based phase matching use the waveguide geometry to tune the effective indices of the interacting modes, which is especially useful in TFLN, AlGaAsOI, GaP-OI, SiN, and chalcogenide platforms. QPM compensates the accumulated phase error by periodically reversing or modulating the effective nonlinear coefficient, and it remains central to PPLN and TFLN devices [9, 11–16, 37]. Resonant enhancement can also lower the required pump power by increasing the circulating field, but this benefit is accompanied by stronger sensitivity to temperature drift, fabrication variation, and resonance detuning [18, 21, 38–40]. Figure 2 summarizes these main routes.

A useful design lesson follows from this: the highest simulated efficiency is not always the best choice. A sharply phase-matched design can look excellent in simulation and still fail after fabrication if the waveguide width shifts by only a few nanometers. A slightly lower peak-efficiency design may be more valuable if it offers a broader tolerance window, lower coupling loss, or simpler temperature control. Process-aware optimization should therefore include lithographic bias, etch-depth uncertainty, sidewall angle, poling duty-cycle error, and resonator-mode splitting. This practical need explains the growing interest in inverse-design frameworks that evaluate both ideal performance and fabrication robustness [5, 41–45].

Figure 2
Main phase-matching routes used in integrated nonlinear photonics. In practical devices, these routes are often combined to preserve efficiency under fabrication and thermal constraints



5. Device Classes and Application-Driven Requirements

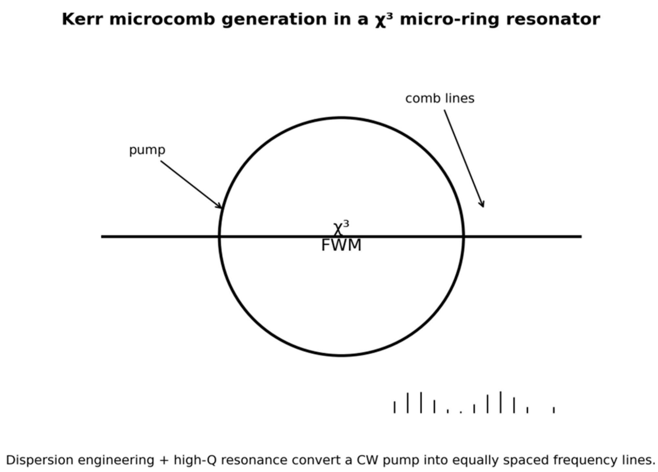
5.1. Frequency conversion and mid-infrared sources

Frequency conversion devices often rely on platforms that combine confinement with flexible phase matching. TFLN is especially suitable for χ^2-based DFG and OPO devices, including tunable mid-IR sources for molecular spectroscopy [14]. AlGaAsOI can provide strong nonlinear response in very compact resonators, while chalcogenide materials help push nonlinear operation deeper into the mid-IR. The best design depends strongly on the intended use. Spectroscopy benefits from tunability and stable operation; communication systems require low noise and reproducibility; quantum interfaces need wavelength conversion that is efficient but adds as little noise as possible.

5.2. Kerr microcombs and supercontinuum generation

Kerr microcombs arise from χ^3 FWM in high-Q resonators. A continuous-wave pump is converted into a set of equally spaced optical lines, provided that the cavity dispersion, pump detuning, and nonlinear gain support stable comb formation [18, 38–40]. SiN remains a mature platform for this purpose because low loss and reliable dispersion engineering can be combined with foundry-compatible fabrication. AlGaAsOI offers a smaller footprint through stronger nonlinearity, while hybrid TFLN structures add electro-optic tuning and faster control [18, 38–40, 46]. In applications, however, octave-spanning bandwidth is not the only useful measure. Start-up reliability, phase noise, line-spacing control, thermal stability, and packaging robustness often decide whether a comb source is usable outside the laboratory. Figure 3 shows the simplified micro-ring geometry.

Figure 3
Simplified Kerr microcomb generation in a χ^3 micro-ring resonator coupled to a bus waveguide

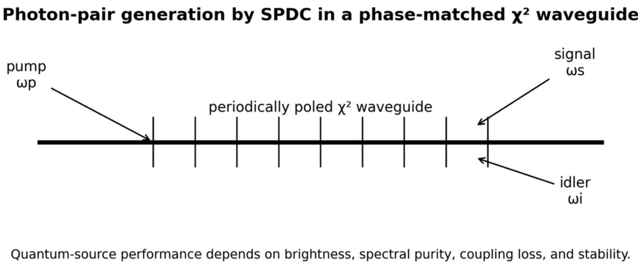


SCG follows a similar balance between nonlinearity and dispersion. In SiN and chalcogenide waveguides, engineered group-velocity dispersion allows SPM, Raman effects, and soliton dynamics to broaden the spectrum [2, 25, 26]. For practical use, a broad spectrum alone is not enough. The output must be sufficiently flat and repeatable, the pump requirements must remain realistic, and the waveguide must tolerate thermal load and optical intensity without degradation.

5.3. Quantum photonics

Nonlinear quantum photonics uses χ^2 and χ^3 processes to generate and manipulate nonclassical states, including photon pairs, squeezed states, and frequency-converted quantum signals. TFLN and PPLN are widely used for SPDC because QPM enables efficient pair generation and spectral tailoring, while the electro-optic response of lithium niobate provides rapid tuning [11]. AlGaAs and InGaP can produce compact, bright sources because of their strong confinement and large nonlinear response. SiN, by contrast, supports χ^3 spontaneous FWM with very low propagation loss and mature photonic integration [5, 11, 24, 47]. A representative χ^2 photon-pair generation scheme is shown in Figure 4.

Figure 4
Photon-pair generation by spontaneous parametric down-conversion in a χ^2 periodically poled waveguide



The comparison between these platforms is not simply a comparison of brightness. TFLN is strong for phase-matched χ^2 processes and active control, but periodic poling, coupling, and packaging must be reproducible. AlGaAs and InGaP can shorten the device length and increase interaction strength, although wafer-scale uniformity remains harder to guarantee. SiN has weaker intrinsic nonlinearity, yet its low loss and scalability become decisive when many sources, filters, interferometers, and routing elements must be integrated on the same chip. The preferred platform therefore depends on the required spectral purity, telecom compatibility, pump efficiency, source brightness, and manufacturability [5, 11, 47].

5.4. Nonlinear metasurfaces and flat nonlinear optics

Nonlinear metasurfaces use resonant nanoantennas to increase local fields while controlling symmetry and wavefront shape in an ultrathin layer [32–35]. Compared with a bulk nonlinear crystal, a metasurface can tailor phase, polarization, emission direction, and resonance through the arrangement of subwavelength meta-atoms. This makes it attractive for compact harmonic generation, nonlinear imaging, and quantum-photonic components. The limitation is that the interaction length is very short and losses can be high, especially in plasmonic designs. Recent inverse-designed metasurfaces show that topology optimization can improve SHG efficiency and directional control while also including fabrication tolerance in the design step [44, 45].

5.5. All-optical signal processing and computing

Integrated nonlinear photonics is also being explored for optical information processing. Kerr phase shifts, parametric gain, bistability, and programmable wave mixing can support functions such as optical logic, pulse shaping, reservoir computing, and photonic acceleration. The challenge is not only to observe a nonlinear effect but also to make it operate with low energy, stable biasing, trainability, and tolerance to fabrication spread. Reconfigurable on-chip nonlinear photonics, based on programmable spatial distributions of effective χ^2, is one possible route beyond fixed-function nonlinear circuits [48].

6. Measurement, Benchmarking, and Reporting Standards

Measurement is one of the most difficult parts of nonlinear photonics because the reported value does not always represent the material response alone. It can change with the measurement method, sample geometry, optical alignment, pump-power calibration, and even the way the data are fitted. For example, Z-scan measurements are still widely used to estimate n_2 and nonlinear absorption in bulk and thin-film samples [6, 7], while the Kurtz-Perry powder method gives a rapid indication of second-order nonlinear activity in crystalline powders [8]. These techniques are useful, but integrated photonic devices introduce additional complications. In a waveguide or resonator, the measured nonlinear signal is affected by optical confinement, resonant field buildup, coupling loss, local heating, modal overlap, and scattering. Therefore, high conversion efficiency should not be treated as conclusive evidence of a larger intrinsic nonlinear coefficient. Linear optical baselines must also be separated from nonlinear signals: for example, laser-synthesized Au@Fe_2O_3 nanoparticles show synthesis-energy-dependent UV–visible absorption without that variation itself establishing a nonlinear mechanism [49].

This point becomes even more important in tightly confined waveguides and high-Q resonators. Parameters such as n_2, d_eff, β_TPA, and χ^2 or χ^3 can only be interpreted correctly when the material contribution is separated from device-related enhancement. A small mode area, for instance, can increase the optical intensity and make the nonlinear response appear stronger, while a resonator can increase the circulating power without changing the material itself. For this reason, experimental papers should report the basic device and measurement details clearly. These include the waveguide width and thickness, effective mode area, propagation loss, launched pump power, estimated on-chip power, input and output coupling losses, loaded and intrinsic Q factors, polarization state, detuning condition, operating temperature, and the exact normalization used for conversion efficiency. Without this information, comparisons between TFLN, SiN, AlGaAsOI, GaP, chalcogenide, ENZ, and metasurface devices may lead to unfair or misleading conclusions [3, 5–8, 50].

Thermal behavior also needs closer attention, especially in resonant nonlinear systems. A device may initially show strong conversion, but this performance can change once optical heating shifts the cavity resonance away from the pump wavelength. In some cases, the system may enter a bistable regime, where the measured output depends on the direction of the pump-power sweep. This means that an apparent increase in efficiency may come from improved resonance alignment rather than from a genuinely stronger nonlinear interaction. Future studies should therefore include details on long-term stability, hysteresis, pump-power sweep direction, wavelength drift, thermal tuning method, and repeatability across several devices or wafer positions. Reporting these points would make platform comparisons more reliable and would help move nonlinear photonic devices from isolated demonstrations toward manufacturable technologies. Table 2 summarizes a minimum set of parameters that should be included in future integrated nonlinear photonic measurements.

7. Inverse Design, Machine Learning, and Programmable Nonlinear Optics

Inverse design and machine-learning-assisted optimization have become important because nonlinear device performance rarely depends on one variable. Phase matching, mode overlap, group-velocity dispersion, Q factor, coupling efficiency, thermal stability, and fabrication tolerance all interact. Manual parameter sweeps remain useful for simple geometries, but they can miss designs that offer a better compromise between efficiency and robustness. Adjoint optimization, topology optimization, Bayesian search, and neural surrogate models can explore wider design spaces while including fabrication constraints and multiple objectives [5, 41].

Recent studies show that these methods are no longer only theoretical. Jia et al. [42] used inverse design to develop an interpretable cavity for integrated nonlinear and quantum photonics. Yang et al. [43] applied dispersion-targeted nanophotonic design to nonlinear and quantum-light generation in silicon carbide Fabry–Perot cavities. Mann et al. [44] used inverse design for nonlinear polaritonic metasurfaces with enhanced SHG, and Stich et al. [45] later introduced fabrication-tolerant topology optimization for all-dielectric nonlinear metasurfaces. Together, these examples show that inverse design is beginning to influence experimentally relevant nonlinear device engineering.

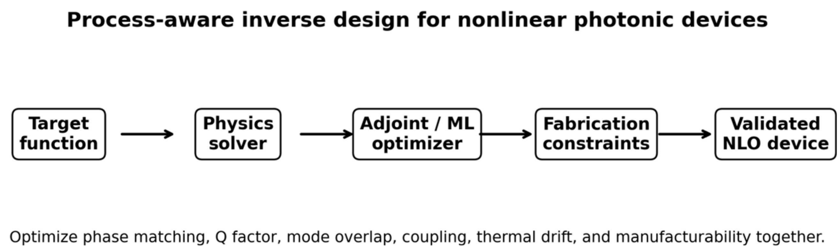
Programmable nonlinear optics is related to inverse design, but it addresses a different limitation. In a conventional device, the spatial distribution of χ^2 or χ^3 is fixed at fabrication, so the wave-mixing function is largely predetermined. Programmable approaches try to modify the nonlinear interaction after fabrication through electric fields, optical writing, phase-change materials, carrier injection, or spatially patterned tuning. Yanagimoto et al. [48] demonstrated a reconfigurable two-dimensional distribution of effective χ^2 inside a waveguide, pointing toward nonlinear circuits whose function can be updated. Other examples include hybrid Kerr-electro-optic combs on TFLN, where soliton generation is combined with electro-optic control [46], and reconfigurable chalcogenide microresonators, where post-fabrication dispersion tuning adjusts the phase-matching condition [27].

For manufacturable nonlinear photonics, the most useful direction is to combine physics-based optimization with uncertainty-aware design. A good inverse-design workflow should not only maximize ideal conversion efficiency but also reduce sensitivity to line-edge roughness, poling duty-cycle errors, sidewall angle variation, thermal drift, and coupling mismatch. In this role, inverse design becomes a bridge between electromagnetic theory and fabrication reality. Future workflows are likely to combine optical simulation, thermal modeling, process data, and wafer-level feedback, so that each fabrication run improves the next design cycle [5, 41–45]. Figure 5 summarizes this process-aware workflow.

Table 2
Suggested reporting parameters for integrated nonlinear photonic measurements

Quantity to report	Why it matters	Minimum recommended description
On-chip pump power	Separates device efficiency from fiber-chip coupling loss	State launched power, coupling loss, and estimated power inside the nonlinear section
Propagation loss and Q	Determines interaction length and resonant enhancement	Report loss in dB/cm or dB/m; for cavities give loaded and intrinsic Q
Mode area and overlap	Controls effective nonlinearity	Provide simulated mode profiles and overlap integrals for interacting waves
Thermal conditions	Affects resonance and phase matching	Report temperature, tuning method, drift, and hysteresis during power sweeps
Normalization of efficiency	Prevents inflated comparisons	Specify whether efficiency is external, internal, normalized, or absolute
Fabrication statistics	Links performance to manufacturability	Include number of measured devices, wafer variation, and tolerance sensitivity if available

Figure 5
Process-aware inverse-design workflow linking simulation, uncertainty, fabrication, and experimental feedback



8. Platform Trade-Offs and System-Level Comparison

Platform selection is best treated as a system-level trade-off rather than a ranking of nonlinear coefficients. TFLN is not automatically the best choice only because it has a strong χ^2 response. SiN is not automatically weak only because it lacks a native χ^2 nonlinearity. ENZ materials and metasurfaces are not automatically practical only because they show very large local-field enhancement. What matters is how nonlinear strength, loss, phase control, thermal behavior, coupling, fabrication yield, and application requirements work together in the final system. Table 3 gives a consolidated comparison, and Figure 6 provides a qualitative map of nonlinear strength versus low-loss maturity.

9. Reliability, Packaging, and Manufacturability

Most integrated nonlinear photonic devices are first evaluated under conditions that are much more controlled than those of a real product. In the laboratory, the coupling can be tuned carefully, the chip temperature can be stabilized, and the pump power can be adjusted until the best response is obtained. A deployed system is different. It may face temperature drift, vibration, mechanical stress, repeated assembly steps, and gradual aging over months or years. A device that performs well on an optical

Figure 6
Qualitative platform map comparing relative nonlinear strength or field enhancement with low-loss maturity

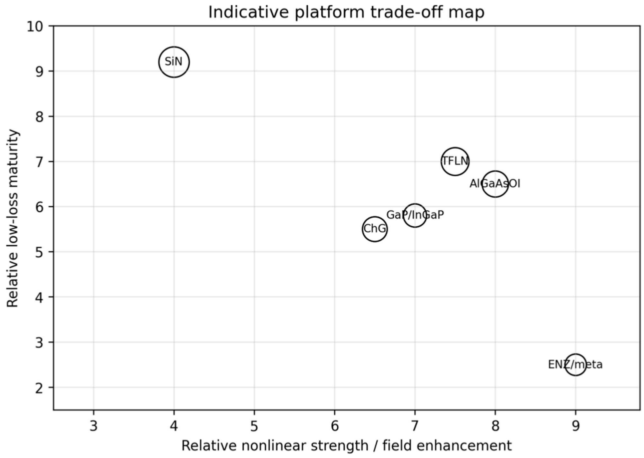


table therefore still needs additional engineering before it can be considered robust.

Packaging and reliability engineering are the bridge between a good demonstration and a usable system. Fiber-to-chip

Table 3
Consolidated platform trade-off table with representative loss/limitation and demonstrated-performance context

Platform	Useful nonlinear feature	Main practical limitation/design note
Bulk lithium niobate (bulk LN)/PPLN	Strong χ^2 response; $d_{33} \approx 25$–27 pm/V; mature SHG, DFG, and OPO operation [1, 4, 15, 37]	Very reliable as a material platform, but the footprint and external coupling are less suitable for dense integrated circuits
TFLN/LNOI	Large χ^2 combined with tight confinement, electro-optic control, sub-µm QPM, visible SHG, mid-IR OPOs, and integrated quantum sources [4, 9–14, 16, 17, 37]	Etch reproducibility, poling fidelity, thermal drift, coupling, and packaging still control the practical yield
SiN	Moderate χ^3 but very low loss and high-Q resonance; useful for Kerr combs, supercontinuum generation, parametric gain, and low-noise integrated photonics [5, 18–20, 38–40]	Lower intrinsic n_2 than III–V or chalcogenide platforms, and thick-film stress can complicate fabrication
AlGaAsOI	High χ^2/χ^3 and strong confinement; compact resonators have enabled efficient Kerr-comb operation and high-Q nonlinear devices [21, 47]	Performance is sensitive to bonding quality, sidewall roughness, thermal handling, and wafer-scale yield
GaP-OI/InGaP	Strong χ^2 with visible-to-telecom compatibility; promising for compact nonlinear conversion and entangled-photon generation [22–24]	The platform is less mature than SiN or TFLN; coupling repeatability and visible-band scattering remain device-dependent
Chalcogenides	High n_2 with mid-IR transparency; useful for supercontinuum generation, high-n_2 waveguides, and reconfigurable GeSbS microresonators [25–27]	Thermal stability, film processing, and integration with foundry-compatible workflows remain important limitations
ENZ oxides/metasurfaces	Very large effective nonlinearities from field enhancement; useful for enhanced SHG/THG, nonlinear beam shaping, THz metasurfaces, and inverse-designed flat nonlinear optics [28–36, 44, 45]	External efficiency can be limited by absorption, heat, short interaction length, and large-area nonuniformity

coupling is a clear example. The optical mode of a standard single-mode fiber is much larger than the mode of a tightly confined integrated waveguide, so a poorly designed interface can waste a large fraction of the input and output power. Spot-size converters, edge couplers, or grating couplers can reduce this penalty, but losses of several dB per facet are still common in many nonlinear photonic circuits. Under those conditions, the external conversion efficiency may be limited more by coupling loss than by the intrinsic nonlinear efficiency of the waveguide.

Thermal control is equally important, especially for resonant devices. A microresonator must remain spectrally aligned with the pump laser; even a small temperature shift can move the resonance, lower the circulating power, and weaken the nonlinear process. In TFLN, the thermo-optic response of $LiNbO_3$ can also shift the phase-matching condition. Active thermal stabilization is often used to correct these effects, but it adds control electronics, power consumption, and packaging complexity. This is why a device-level efficiency value is incomplete unless thermal stability is also considered.

The dominant manufacturing concern changes from one platform to another. In TFLN, reproducible etching and high-fidelity periodic poling over large chip areas are central. In SiN, the challenge is to manage stress in thicker films while preserving ultralow loss under foundry-compatible deposition. For III–V platforms, bonding quality and sidewall roughness are often limiting. Chalcogenides require careful control of thermal stability and heterogeneous integration. ENZ and metasurface devices face the additional problem of achieving uniform response over large areas [3, 5, 11, 17, 20, 27].

Moving nonlinear photonics toward manufacturing will require wafer-scale process control, statistical testing across many devices, low-loss and repeatable coupling schemes, and thermal management included from the start of the design. Hybrid architectures are likely to become important: passive routing may be handled by low-loss SiN, nonlinear conversion by TFLN or III–V sections, and modulation or detection by materials optimized for those functions. Such combinations are promising, but they also make the integration problem harder because every interface introduces possible loss, reflection, thermal mismatch, or yield reduction. Figure 7 summarizes the associated manufacturing and packaging bottlenecks.

10. Outlook and Future Research Directions

Nonlinear photonics has reached a point where the basic physical mechanisms are no longer the main barrier. The principal material platforms are known, and many impressive devices have already been demonstrated. The harder question is now practical: how can these results be turned into stable, reproducible, and affordable systems that work outside carefully controlled laboratory conditions?

More robust phase matching is one of the clearest needs. In χ^2 platforms, this means better control of periodic poling, domain uniformity, and waveguide geometry under realistic foundry tolerances. A small error in width, thickness, or refractive index can move the device away from the intended phase-matching point and reduce efficiency. In χ^3 platforms, the same issue appears mainly through dispersion. The fabricated dispersion profile must stay close to the designed one; otherwise, FWM, soliton dynamics, and Kerr-comb formation can change substantially. For ENZ materials and metasurfaces, the task is to turn strong local-field enhancement into useful external efficiency rather than leaving the enhancement confined to a very small near-field region.

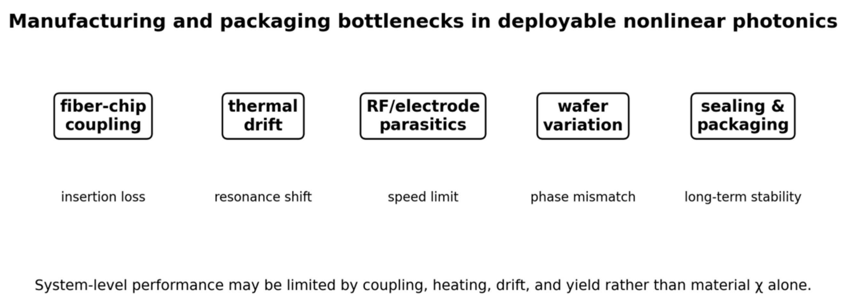
Clearer benchmarking is another priority. At present, different studies often report different quantities, normalize efficiencies in different ways, or omit important experimental details. A useful comparison should include conversion efficiency together with propagation loss, coupling loss, Q factor, pump power, thermal conditions, device length, mode area, fabrication variation, and stability over time. Without these details, one device can look highly efficient in isolation but remain difficult to compare with another platform under realistic operating conditions. More consistent reporting would make the literature easier to interpret and would help identify which approaches are genuinely scalable.

Future progress will also depend on inverse-design and machine-learning tools becoming easier for device engineers to use. These methods are powerful, but they should not remain confined to specialist computational groups. Practical design tools must be physically reliable, computationally manageable, and able to include fabrication constraints from the beginning. The next step is not only to search for an ideal geometry but also to predict how that geometry behaves when line-edge roughness, etch bias, material dispersion, thermal drift, and coupling errors are present. In this sense, inverse design must move from perfect-device optimization toward fabrication-aware design.

Nonlinear devices will also need to be designed around their final application. A dual-comb spectroscopy source needs broad and stable spectral coverage. A quantum frequency converter must emphasize low noise, high fidelity, and efficient wavelength translation. A coherent communication transmitter requires compatibility with high-speed modulation and low power consumption. An optical neural-network accelerator may instead prioritize dense integration, parallel operation, and tolerance to device-to-device variation. These examples show that the best nonlinear platform is not fixed; it changes with the system function.

Overall, nonlinear photonics is moving from a material-centered field toward a system-centered technology. Strong intrinsic nonlinearity will remain important, but it will not be enough on its own. The platforms with the largest long-term impact will be those that can be fabricated reproducibly, integrated with other photonic and electronic components, packaged

Figure 7
Manufacturing and packaging bottlenecks that may limit nonlinear photonic systems even when the intrinsic nonlinear response is strong



reliably, and operated under real environmental conditions. This problem is more difficult than maximizing a single coefficient or efficiency value, but it is the problem that must be solved for nonlinear photonics to become a deployable technology.

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

Raneen Salam: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Haneen Abass Alrubaie:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Ghasaq A. Tomaa:** Validation, Investigation, Writing – review & editing. **Samah A. Al-Heeti:** Investigation, Data curation, Writing – review & editing, Visualization.

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