REVIEW

Parametric Generation of Tunable Light from Continuous-Wave to Femtosecond Pulses

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By exploiting nonlinear optical effects, a technology of unprecedented flexibility for the production of tunable coherent light has been developed. Referred to as optical parametric generation, it provides sources with spectral coverage extending all the way from the ultraviolet to the mid-infrared, and with temporal coverage extending over all time domains from the femtosecond pulse to the continuous wave. Such sources generate coherent light of outstanding optical quality and are now finding wide-ranging applications.

The development of nonlinear optical techniques for the generation of light of new wavelengths rapidly followed the discovery of the laser (1960), which provided the high-intensity light necessary for such processes. In 1965, Wang and Racette demonstrated the nonlinear process in which light beams of two different frequencies are mixed together in a nonlinear crystal to generate a new light beam with a frequency equal to the difference in the two original frequencies. This process of difference-frequency mixing underpins optical parametric generation. In the same year, a pulsed optical parametric oscillator (OPO) was demonstrated by Giordmaine and Miller (*1*), to be followed in 1968 by the demonstration of continuous-wave OPOs independently by Byer *et al.* (*2*) and Smith *et al.* (*3*). Extension of these techniques to the shorter time domains of pico- and femtoseconds awaited the development of suitable pump lasers in the late 1980s.

Although the basic principles behind optical parametric generation (*4*) have been known since these early days, it has taken over 30 years for the full potential of the approach to be realized (Fig. 1). The current renaissance has come about through a combination of advances encompassing new optically nonlinear materials and their fabrication at the microstructure level; new pump lasers, in particular all-solid-state and ultrashort-pulse devices; and novel optical cavity configurations. Optical parametric generators (OPGs), many variants of which are now commercially available, are currently finding a burgeoning range of applications in, for example, spectroscopy; medical diagnostics and therapies; physical, chemical, biophysical, and biomolecular research; environmental monitoring; defense and security; and optical communications.

Basic Principles: Optical Gain, Nonlinear Materials, and Phase Matching

When light passes through a medium (for example, a glass window), its wavelength is unchanged. Of course, if the glass is colored and if different wavelengths are already present in the light, they may be differentially absorbed to change the overall color effect. However, in this process, light that is initially of one wavelength is not converted into light of another wavelength. This is the realm of linear optics, in which the medium responds linearly to the instantaneous value of the oscillating electric field associated with the light. However, at high light intensities, such as those available from lasers, a purely linear response may no longer apply. Consider in particular the case where the response (namely, the polarization) of the medium exhibits a nonlinear component proportional to the square of the instantaneous electric field of the light. Further suppose that two light beams are present, one of frequency ω_1 and electric field strength E_1, and the other of frequency ω_2 and electric field strength E_2. The response of the medium [oscillating polarization (P) induced in the medium] now has a component of the form

$$P \sim d_{\text{eff}}[E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t)]^2 \quad (1)$$

where t is time, and d_{eff} is a measure of the strength of this nonlinear response in the particular material (and is referred to as the effective nonlinear coefficient).

It can then be seen that the induced oscillating polarization has a component at the difference frequency ($\omega_2 - \omega_1$), namely

$$P(\omega_2 - \omega_1) = \tfrac{1}{2} d_{\text{eff}} E_1 E_2 \cos[(\omega_2 - \omega_1)t] \quad (2)$$

This component radiates a new light wave at this difference frequency ($\omega_2 - \omega_1$). Table 1 lists values of d_{eff} (in picometers per volt, where 1 pm = 10^{-12} m) for some important optically nonlinear materials, along with their other important optical properties.

The above nonlinear process is exploited twice over in optical parametric generation, where the higher frequency light wave (ω_2) is very much more intense than the lower frequency light wave (ω_1). The former is now referred to as the pump wave (frequency designated by ω_p) and the latter as the signal wave (frequency designated by ω_s). A non-

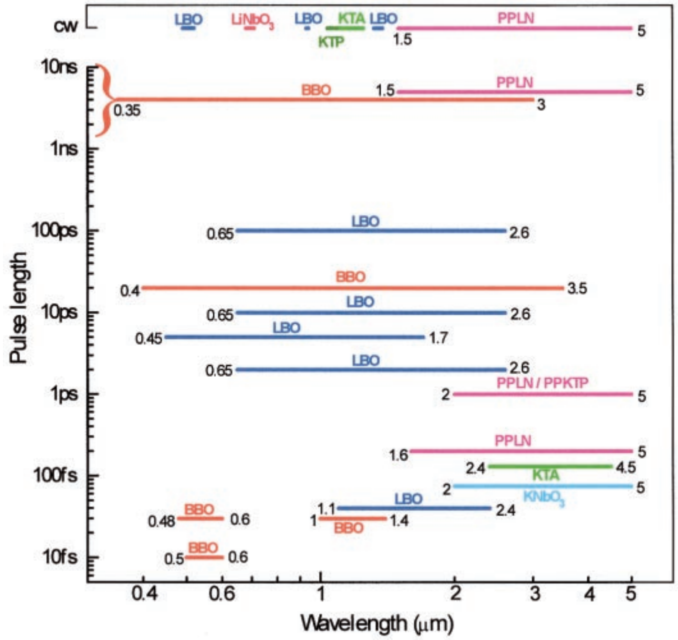

Fig. 1. Spectral (horizontal axis) and temporal (vertical axis) coverage provided by OPGs. LBO, dark blue; BBO, red; PPLN, purple; KTA, light green; $KNbO_3$, light blue; PPKTP, purple; and KTP, dark green. The numbers at the beginning and end of each bar designate the limits of the tuning ranges attained with the respective material.

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linear medium immersed in a high-intensity pump wave (ω_p), and with a low-intensity signal wave (ω_s) also incident on it, generates a new wave, namely the difference frequency wave at a frequency ($\omega_p - \omega_s$), referred to as the idler wave (ω_i). However, because the pump wave is so intense, this idler wave grows rapidly and goes on to interact with the pump wave in a further step and via the same nonlinear process as before, so as to generate more signal wave. Hence, the medium exhibits optical (parametric) gain for the signal wave, amplifying this initially weak wave, and a new wave, the idler wave, is generated, all at the expense of the strong pump wave, which is depleted in the process. This arrangement is referred to as an optical parametric amplifier.

In the OPO, the nonlinear medium, immersed in the focused pump wave, is located within an optical cavity (Fig. 2A). Cavity resonance corresponds to an integral number of half wavelengths of the light (the signal wave, say) fitting between the mirrors. Optical noise within the cavity at a frequency corresponding to such a resonance provides the initial input. If the parametric gain exceeds the losses associated with the cavity, this noise is progressively amplified on multiple passes through the nonlinear medium, building up into a coherent signal wave with an associated idler wave. A fraction of the signal wave (and the entire nonresonant idler wave) may be coupled out of the cavity for subsequent use. The roles of the idler and signal waves may be interchanged, which is appropriate if radiation at the (shorter) signal wavelength is required for external use rather than at the (longer) idler wavelength. Increasing the distance between the mirrors while maintaining the same number of half wavelengths increases the resonant wavelength in proportion, providing fine-tuning of both wavelengths. An optical cavity may be designed to resonate both signal and idler waves simultaneously [a doubly resonant cavity (Fig. 2C)].

Table 1. Properties of some important nonlinear materials (the damage thresholds are for 10-ns pulses at 1 μm).

Nonlinear medium	d_{eff} (pm/V)	Transparency range (μm)	Damage threshold (GW/cm²)
KDP (potassium dihydrogen phosphate)	0.5	0.22–1.1	1
Li NbO_3 (lithium niobate)	6	0.35–4.5	0.1
BBO	2	0.19–3.0	5
LBO	1	0.16–2.5	10
KTP	3	0.35–3.5	0.5
$AgGaSe_2$ (silver gallium selenide)	60	0.8–18	0.03
PPLN	14	0.33–5	0.1
PPKTP	5–10	0.35–3.5	0.5
$KNbO_3$	18	0.4–5.5	0.2

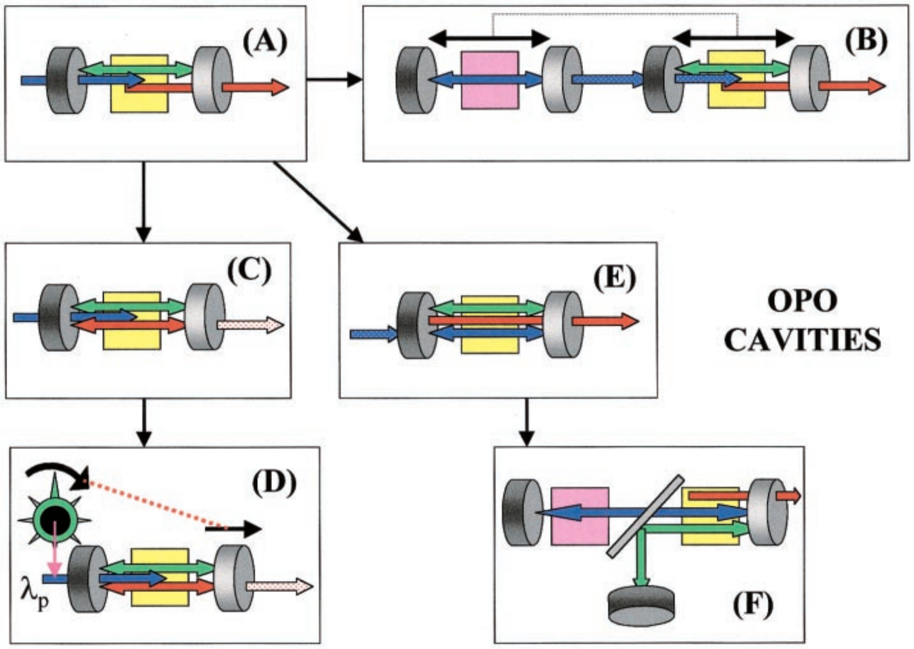

Fig. 2. Cavity configurations for OPOs. (**A**) Singly resonant. (**B**) Synchronously pumped. (**C**) Doubly resonant. (**D**) Doubly resonant with pump tuning. (**E**) Pump-enhanced. (**F**) Intracavity. Blue, green, and red arrows designate pump, signal, and idler waves, respectively. A double-ended arrow indicates that the wave is resonant in the cavity. The nonlinear medium is shown in yellow and the gain medium in purple. Dotted lines indicate servocoupling; dot-patterned arrows indicate components of resonated waves external to the cavity.

Phase matching is of vital importance in optical parametric generation, where the wavelength of light is much smaller than the dimensions of the nonlinear medium. The induced oscillating polarization is distributed along the whole path of the light beam in the medium (Fig. 3A). Thus, there is an array of sources, rather than just one source. For maximum effect, the contributions from all of these sources must add together constructively (in phase) at the output of the nonlinear medium (Fig. 3B). If the radiation from the different sources progressively changes phase, destructive interference can occur, diminishing the total intensity of the newly generated light (Fig. 3C). A criterion for phase matching may be deduced (*4*) as

$$\omega_p n_p = \omega_s n_s + \omega_i n_i \qquad (3)$$

where n_p, n_s, and n_i are the refractive indices of the nonlinear medium at the pump, signal, and idler wavelengths, respectively.

Using crystal birefringence (of a magnitude selected by appropriate choice of propagation direction) to offset dispersion can satisfy the above condition for a particular frequency combination, a technique known as birefringent phase matching (BPM). Altering the propagation direction changes the selected frequency combination, leading to angle tuning. Changing the crystal temperature may also differentially alter refractive indices, resulting in temperature tuning.

In 1994, the technique of quasi–phase matching (QPM) proposed by Bloembergen in 1962 was brought to practical realization (*5*) through the use of periodically poled (PP) nonlinear materials and has had a radical impact on nonlinear optics. In the absence of BPM, a maximum in the amplitude of the generated wave is reached when a phase difference of π has accumulated (Fig. 3C). If after this distance, known as the coherence length, the material is altered so that the next component of the generated wave is added with a phase difference π compared to that of the immediately preceding component, then constructive addition continues and the generated wave continues to grow (Fig. 3D). One technique for abruptly altering the phasing of the generated wave is to produce a domain inversion in the nonlinear crystal after a distance equal to the coherence length (Fig. 3E) and to continue with the process in a periodic fashion (periodic grating), a technique known as periodic poling (*5*). QPM allows an extensive range of signal and idler frequency combinations to be accessed in a particular material by changing the grating period, and because specific propagation directions in the crystal are not now required, it allows the largest values of d_{eff} associated with the material to be used (Table 1). So far, the nonlinear material lithium niobate has been the major player (PPLN), but other options include the periodically poled phosphates and arsenates of the KTP (potassium titanyl phosphate) type (PPKTP, and so on) (*6*).

Nanosecond-Pulse OPOs

The development of the nonlinear crystal beta-barium-borate (BBO) in 1987, followed by that of lithium triborate (LBO) in 1989, stimulated the development of these devices. Key features of the borates are wide transparency ranges and high resistance to optical damage, particularly in the ultraviolet (UV), and as such they complement KTP, an excellent material for the near infrared (IR).

A 1-cm-long BBO crystal pumped in the UV (355 nm) at an intensity of 0.04 GW cm^{-2} (one-10th that of optical damage) exhibits a single pass gain of about 8 (*7*). For a coherent optical pulse to grow from noise, a total gain of about 140 dB is required, hence light must traverse the crystal about 15 times. If the length of the cavity is twice that of the crystal, the time required for buildup is approximately 2 ns, which is compatible with 5- to 10-ns pump pulses.

The pulsed (Q-switched) Nd laser has proved to be a highly effective and flexible pump source for this class of OPO; when used directly (a 1064-nm pump) or after frequency doubling (a 532-nm pump) or frequency tripling (a 355-nm pump). Spectral ranges covered include KTP pumped at 532 nm (*8*) with a signal wave at 700 to 920 nm and an idler wave at 1.3 to 2.2 μm, and BBO pumped at 355 nm (*9*, *10*) with a signal wave at 426 to 710 nm and an idler wave at 710 to 2120 nm. By using a grating for wavelength selection within the OPO cavity, a single-frequency source with a linewidth <200 MHz, which is close to the transform limit (*11*), and capable of continuous frequency scanning over 100 cm^{-1} anywhere within the ranges from 700 to 900 nm and 1.4 to 2.2 μm has been developed (*8*). Injection seeding, either by tunable diode lasers to control the idler wave bandwidth (*12*) or by a master oscillator OPO to control the bandwidth of a slave oscillator OPO (*13*), has also proved successful in attaining single-frequency operation. Diode laser–pumped solid-state lasers (DPSSLs), in particular the Nd laser, in which diode lasers replace flashlamps, have been used as pumps for OPOs, resulting in compact sources of widely tunable coherent radiation (*14*). More recently, QPM nonlinear materials (PPLN and PPKTP) have reduced oscillation thresholds in IR OPOs (1 to 4.5 μm) to the range 10 to 100 μJ, allowing microchip lasers (*15*), erbium-doped fiber lasers (*16*), and miniature high-repetition rate DPSSLs (*17*) to be used as pump sources. Many commercial versions of nanosecond-pulse OPOs are now available, and they are widely used in spectroscopy.

Picosecond and Femtosecond OPOs

Because light travels a distance of only 300 μm in 1 ps, it is generally not possible for the down-converted light to traverse the nonlinear medium many times, and thereby buildup from noise, within the time duration of a single picosecond pulse. In 1989, the technique of synchronous pumping, first demonstrated in parametric devices in 1972 (*18*), was further developed to overcome this limitation (*19*). In this technique, many consecutive pulses from the pump laser sequentially pump one circulating pulse within the cavity of the OPO. The interval between the arrival of adjacent pump pulses (equal to the round-trip time of the pump laser cavity) is arranged to match the round-trip time of the down-converted pulse within the OPO cavity, so that the two pulses always meet in the nonlinear medium; that is, the cavities are synchronous (Fig. 2B). The rapid development of new mode-locking techniques (additive pulse mode-locking and self mode-locking), coupled with advances in nonlinear materials, have resulted in the development of many practical schemes for both pico- and femtosecond pulse generation. To a first approximation, the duration of the pump pulses determines the duration of the down-converted pulses from the OPO. The duration of the former is determined by the accessible gain bandwidth of the active medium of the pump laser (*11*), and the gain bandwidth of the OPO (phase-matched bandwidth) must equal or exceed this if pulse broadening is not to occur on down-conversion.

The single-pass gain of the down-converted pulse in passing through the nonlinear medium must exceed the single-pass loss of the OPO cavity. Because the parametric gain is determined by the peak intensity of the pump pulse, this condition is readily fulfilled. For example, for a nonlinear medium with a d_{eff} of 1 pm/V and a length of 20 mm (LBO), pumped by a train of pulses of wavelength 0.5 μm, energy 1 nJ, and duration 1 ps (peak power, 1 kW), a gain of >100% per pass is expected (*7*).

An efficient synchronously pumped picosecond OPO was demonstrated in 1989 using a conventional flashlamp-pumped mode-locked Nd laser as a pump (*20*). [The gain bandwidth of 100 GHz in Nd limits minimum pump pulse durations to 1 to 2 ps (*11*).] However, it has been the development of DPSSLs, in particular those based on Nd, that has driven rapid progress in this area over the past decade. The use of a DPSSL (a mode-locked, Q-switched Nd:YLF laser, frequency-doubled to 523 nm) to synchronously pump an OPO ($\mathrm{LiNbO_3}$) was demonstrated in 1990 (*21*), although it was restricted to the generation of finite-duration trains of picosecond pulses. Continuous generation was reported in 1992 (*22*, *23*). Extension to a wide range of nonlinear materials (KTP, LBO, and PPLN) has progressively improved performance and extended tuning ranges. For example, a device based on PPLN and pumped at 1 μm by a mode-locked Nd laser (DPSSL) generates pulses of 2 ps duration at a 120-MHz

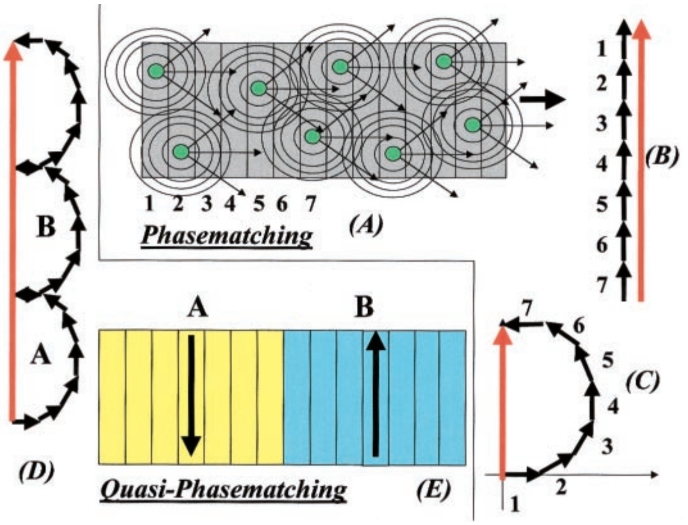

Fig. 3. Phase matching in nonlinear media. (**A**) The signal (or idler) originates from sources (numbers 1 through 7) distributed throughout the medium. (**B**) Phase matching. (**C**) Absence of phase matching. (**D**) Quasi–phase matching. (**E**) Domain inversion.

repetition rate, with a down-conversion efficiency of 75%, and is tunable over 2.2 to 6.3 μm on the idler wave and 1.67 to 2.2 μm on the signal wave, with maximum mean output powers of 150 mW (idler) and 500 mW (signal) (*24*).

An alternative pump laser is the titanium sapphire laser (Ti:S laser). The discovery of self mode-locking in 1991 in this laser provided an ideal source for the synchronous pumping of OPOs on pico- and femtosecond time scales. A particular advantage here is the flexibility of tuning the OPO by tuning the pump laser. In 1993, 1.2-ps pulses were generated in KTP at 82-MHz repetition rates using such a laser (*25*). Tuning the Ti:S laser over the range from 720 to 853 nm resulted in a signal tuning range of 1.05 to 1.21 μm and an idler tuning range of 2.28 to 2.87 μm, with total down-converted powers of 700 mW (42% efficiency). A range of nonlinear materials has subsequently been explored, including LBO (*26*), PPLN (*27*), and PP rubidium titanyl arsenate (PPRTA) (*28*). Including a further nonlinear crystal (LBO) within the cavity of the OPO (itself based on LBO) for intracavity second-harmonic generation of the signal wave extended spectral coverage to the visible (584 to 771 nm) (*29*).

In extending the synchronous cavity technique to the femtosecond (100 fs and below) regime, additional processes need to be considered. The difference in the group velocities of the pump and the signal (or idler) pulses in the nonlinear crystal leads to group velocity walkoff (GVW), in which one pulse separates from the other in time (*30*). Because typical values for GVW are 10 to 100 fs/mm, the length of a crystal must not exceed 1 to 10 mm when it is required to generate sub–100-fs pulses. As a result, although mean power requirements are similar, femtosecond OPOs make more demands than do picosecond OPOs on nonlinear materials' resistance to optical damage. Other issues include extended gain bandwidth to support the shorter duration pulses and more stringent control of cavity lengths to achieve synchronism.

In 1992, femtosecond OPOs pumped by self–mode-locked Ti:S lasers and based on KTP as the nonlinear medium were reported (*31*, *32*). Other BPM nonlinear materials investigated include KTA (*33*), RTA (*34*), $KNbO_3$ (*35*), and CTA (*36*). Typically, spectral coverage of 1 to 5 μm (signal and idler), average powers of 1 to 500 mW, pulse repetition rates of 80 to 350 MHz, and pulse durations of 30 to 300 fs have been reported in such configurations. The roles of self phase-modulation and group velocity dispersion, which lead to both pulse broadening and frequency chirping, have been widely studied (*37*), including soliton effects (*38*). Cascaded intracavity frequency doubling within the OPO cavity itself has extended tuning ranges to the visible (620 to 660 nm) (*39*, *40*). Alternatively, use of a frequency-doubled Ti:S laser to pump the OPO has enabled the direct generation of 30-fs pulses tunable to below 600 nm (*41*). More recently, QPM materials, including both PPLN (*42*, *43*) and PPRTA (*44*), have extended tuning further into the mid-IR (6.5 μm). Many commercial versions of pico- and femtosecond OPOs are now available.

Continuous-Wave OPOs

For a singly resonant OPO (Fig. 2A) to operate continuously [continuous wave (CW)], the single-pass gain must exceed the round-trip fractional power loss of the resonant cavity at all times. For a loss of 1%, a d_{eff} of 3 pm/V, and a crystal length of 10 mm, pump powers in excess of 2.5 W are required to exceed threshold when pumping at 530 nm (*7*). A singly resonant CW OPO was demonstrated in 1993 (*45*) under such conditions, when a minimum oscillation threshold of 1.4 W (reduced by double-passing the pump) was attained. A substantial breakthrough came with the development of PPLN, which when pumped at 1064 nm by a Nd:YAG laser exhibited a threshold of 3.6 W, down-conversion efficiency >90% at 2.5 times threshold, and >1 W of tunable output in the nonresonant idler wave throughout the spectral range from 3.3 to 3.9 μm (*46*, *47*). Pumping PPLN with 532-nm radiation (with a frequency-doubled $Nd:YVO_4$ laser) has extended the tuning range to cover 917 to 1266 nm with generated powers between 200 and 500 mW (*48*). A fan-out grating design has been reported, with which the grating period changes smoothly from 29.3 to 30.1 μm, hence allowing continuous smooth tuning over 350 cm^{-1} at a fixed temperature (*49*). Cascaded sum frequency mixing of the generated signal wave with the residual pump wave within the same PPLN crystal used for down-conversion through incorporation of two in-line gratings of different periods, has provided around 1 W of radiation tunable over 625 to 630 nm (*50*). A PPLN OPO directly pumped by an InGaAs diode laser master oscillator and power amplifier has generated close to 500 mW of single-frequency idler radiation around 2 μm, continuously tunable over >56 GHz by pump tuning (*51*).

Despite the use of QPM materials, singly resonant CW OPOs still show high pump thresholds, and alternative cavity geometries have been explored to address this issue. In the doubly resonant OPO (Fig. 2C), both signal and idler waves build up to high intensity in the nonlinear medium, reducing the gain required to reach oscillation threshold by the reciprocal of the round-trip power loss associated with the additional resonance (*4*). For a loss of 1%, the pump power required reduces by about two orders of magnitude. This allows the newer QPM materials (PPRTA and PPKTP), which have better thermal properties but lower d_{eff}'s than PPLN, to be used. In a doubly resonant OPO, both signal and idler waves are resonant in the same cavity simultaneously, so that altering the distance between the mirrors for fine-tuning requires both wavelengths to either increase or decrease together. However, because the sum of the signal and idler frequencies must at all times equal the pump frequency, the pump laser must be simultaneously fine-tuned to accommodate this and hence maintain oscillation (Fig. 2D). By such means, fine-tuning of single-frequency radiation over bands of 4 to 5 GHz, where adjacent bands may be overlapped to provide a total fine-tuning window of 0.4 THz and where this window may be set anywhere across the phase match bandwidth of the nonlinear crystal, has been demonstrated in doubly resonant oscillators with pump thresholds of a few tens of milliwatts (*52*). PPKTP-based OPOs with grating periods engineered for specific wavelengths of interest to environmental sensing have been assessed in spectroscopic applications (*53*), and a variant of this scheme pumped by a microchip laser has been demonstrated (*54*). A frequency-stabilized doubly resonant OPO has been shown to exhibit Root Allan variances approaching 10 Hz for integration times of the order of hundreds of seconds (*55*).

An alternative approach to low threshold operation is the pump-enhanced scheme (Fig. 2E). Here the OPO cavity resonates both the pump wave, enhancing the pump power and intensity in the nonlinear medium, and one of the down-converted waves. The external pump power required to reach threshold is reduced by the pump enhancement factor. In 1994, a pump-enhanced OPO, based on LBO and pumped in the UV, was demonstrated with enhancement factors of >30 along with single-frequency oscillation and a 30% down-conversion efficiency (*56*). In 1997, a pump-enhanced OPO based on PPLN and pumped by a diode laser–pumped Nd:YAG ring laser at 1064 nm was developed and used in spectroscopy (*57*). In the latter, the external pump power required to reach threshold was just 250 mW, and temperature and grating period tuning provided signal tuning ranges of 1450 to 1990 nm and idler tuning ranges of 2290 to 2960 nm. A continuous tuning range of 2 GHz on the signal wave and 0.5 GHz on the idler wave was obtained with a frequency stability <10 MHz/min, determined by the stability of the pump laser, with nonresonant idler output powers of 140 mW (at 800 mW of pump power).

A further approach to low-threshold CW devices is to locate the singly resonant OPO within the cavity of the pump laser itself (Fig. 2F) so as to access the high-intensity intracavity field present there (typically one to two orders of magnitude greater than that coupled out for external pumping purposes). The singly resonant intracavity OPO is capable of generating the same power in the down-converted waves as in the pump wave under optimum output coupling (100% internal efficiency) (*58*). Practical schemes based on BPM nonlinear materials (KTP and KTA) and on QPM nonlinear materials (PPLN, PPRTA, and PPKTP) have been demonstrated in both Ti:S lasers and Nd lasers. For example, using KTA in the cavity of a Ti:S laser, a down-conversion efficiency approaching 90% was demonstrated in a device that tuned on the signal wave over the range from 1100 to 1120 nm and on the idler wave from 2440 to 2860 nm through pump tuning, with more than 0.5 W of power being obtained in each of the waves simultaneously throughout the entire tuning range (*58*). A compact all-solid-state OPO based on PPLN within the cavity of a Nd:vanadate laser generated 70 mW of nonresonant idler wave over the range 3160 to 4020 nm when pumped by only a 1-W laser diode (*58*).

OPGs

Traveling-wave optical parametric generators allow highly energetic pico- and femtosecond optical pulses to be generated without the need for optical cavities, thereby providing extensive spectral coverage (0.2 to 20 μm) from a single simple device (*59*, *60*). In this approach, a source of parametric superfluorescence (an OPG with optical gain of 10^{10} to 10^{12}) provides the seed pulse (energy 10 to 100 nJ) for subsequent parametric amplification (with an OPG with optical gain of 10^3 to 10^5). The latter gain is such that after only a few passes of the amplifier, the intensity of the down-converted pulse comes to rival the intensity of the pump pulse itself. Progress in this area has depended on the availability of nonlinear materials with a high optical damage threshold (LBO and BBO). Pulse shortening occurs through pump depletion, allowing subpicosecond pulses to be generated from input pulses of a few picoseconds duration. A flexible commercial system is available that generates pulses of 0.2 to 5 mJ energy and 50 fs to 3 ps duration, tunable anywhere over the range from 1.15 to 2.6 μm, and extendable to the range from 300 nm to 20 μm with the addition of optical mixers.

Conclusions

Developments in optically nonlinear materials (in particular those based on quasi–phase matching), refined pump lasers, and novel cavity geometries have seen optical parametric generation fulfill its 30-year promise of providing unrivalled spectral and temporal flexibility in the generation of coherent light (*61*). Commercial systems offering wide tuning ranges from the UV to the mid-IR and from nano- to femtosecond pulse durations are now widely available, and CW sources should become so in the next few years. Intensive efforts to fabricate alternative quasi–phase matched materials, coupled with further progress in device configurations, should drive spectral extension deeper into the UV and IR and permit device miniaturization, including all-solid-state and integrated structures, and further refinements in spectral and temporal control. As a result, further pervasive applications for these sources will follow.

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   $$\text{optical gain} = \cosh^2[\Gamma L],$$

   $$\text{where } \Gamma^2 L^2 = 3 \times 10^4 d_{\text{eff}}{}^2 I_\text{p} L^2/[\lambda_\text{s}\lambda_\text{i} n_\text{s} n_\text{i} n_\text{p}]$$

   L is the length of the nonlinear medium (in meters); I_p is the intensity of the pump light (in watts per square meter); the λ's are wavelengths (in meters); and the n's are refractive indices; with the subscripts s, i, and p referring to signal, idler, and pump waves, respectively. Confocal focusing (light focused so that it doubles in area because of diffraction over the length of the medium) optimizes the gain (*4*) when the above expression reduces to

   $$\Gamma^2 L^2 = 1.5 \times 10^4 d_{\text{eff}}{}^2 P_\text{p} L/[\lambda_\text{p}{}^3 n_\text{s} n_\text{i}]$$

   where P_p is the pump power (in watts) and the wavelengths of the signal and idler are taken equal (degenerate operation). When $\Gamma^2 L^2 \ll 1$, the first equation above becomes

   $$\text{optical gain (\%) per unit of power per unit of length}$$

   $$= 7 \times 10^{-3} d_{\text{eff}}{}^2/\lambda_\text{p}{}^3 (\%/\text{W}\cdot\text{cm})$$

   where d_{eff} is in picometers per volt, the wavelength is in micrometers, and the n's $= 1.5$. One or the other of the above relations is used to calculate the optical gain in specific cases, as appropriate to the circumstances.
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