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978-0-521-86102-1 - Fiber Optical Parametric Amplifiers, Oscillators and Related Devices
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1 Introduction

Fiber optical parametric amplifiers (OPAs) exploit nonlinear optical properties of optical fibers. Their operation is based on the third-order susceptibility $\chi^{(3)}$ of the glasses making up the fiber core. While this nonlinearity is relatively weak in silica-based glasses, the small cross-sections, low loss, and large lengths available with silica-based fibers can lead to sizeable effects, even with moderate pump powers. While silica-based fibers are currently the most widely used, parametric amplification is also possible in any other type of fibers, some of which have very high nonlinearity coefficients. Fiber OPAs have important characteristics, which make them potentially interesting for a variety of applications, as follows.

Gain bandwidth increasing with pump power

In principle, this provides a means for making amplifiers with a bandwidth of several hundred nanometers, while using just one or two pumps. This could provide a substantial bandwidth increase compared with the currently popular erbium-doped fiber amplifiers (EDFAs) and Raman amplifiers (RAs), which have basic bandwidths of the order of tens of nanometers.

Arbitrary center wavelength

The gain region(s) can be centered about any arbitrary wavelength λ_c. The only constraint is that the fiber must have a zero-dispersion wavelength (ZDW) λ_0 close to λ_c. This feature is also available with RAs but not with doped-fiber amplifiers. It could be used for providing gain in regions where practical amplifiers currently are not available.

Large gain

It is relatively easy to obtain a large gain. Continuous-wave (CW) and pulsed gains of 70 dB have been demonstrated in single devices. The fact that the gain exists only for signals propagating in the same direction as the pump is an advantage, as it minimizes the possibility that oscillations will occur between small reflections at the ends of the OPA.

Wavelength conversion

If a signal is injected into a fiber OPA, an amplified signal emerges from the output together with a new wavelength component, the idler. This feature can be used for generating new wavelengths. If the signal is modulated, its modulation is transferred to the idler; this can be used for changing the optical frequency of a signal, which could be a useful operation in communication systems. The conversion of unmodulated waves can also be used for generating wavelengths in regions where suitable light sources are lacking, in a variety of other applications.

An important point is that high signal-to-idler conversion efficiency can be obtained, since it is almost as large as the signal gain and can therefore be as high as 70 dB, even for CW operation. This feature is not available with other wavelength-conversion methods, such as those using semiconductor optical amplifiers (SOAs) or $\chi^{(2)}$ in materials such as periodically poled lithium niobate (PPLN).

Spectral inversion

In fiber OPAs, wavelength conversion is accompanied by spectral inversion, which means that the idler spectrum is symmetric to the signal spectrum with respect to the center frequency. This property can be exploited in communication systems to combat potentially detrimental effects such as dispersion.

Phase conjugation

This is another property of the idler: its phase is opposite to that of the original signal. This can be used for counteracting some nonlinear effects that affect the phase of waves, such as cross-phase modulation.

High-speed optical signal processing

Because the fiber nonlinearity is virtually instantaneous, high-speed modulation of the pump will generally result in modulation of both the signal and the idler. For example, if the pump is intensity modulated, so will be the signal and idler. This can be used for (i) shaping or reshaping signal pulses (regeneration), (ii) demultiplexing high-speed TDM signals, and (iii) optical sampling.

Low noise figure

Fiber OPAs can exhibit noise figures (NFs) below 4 dB, i.e. comparable with those of EDFAs. In addition, when they are operated in a phase-sensitive manner their NFs fall below 3 dB and approach 0 dB, which is of course the best that can be achieved with any type of amplifier.

Unidirectional gain and spontaneous emission

The parametric gain of fiber OPAs is available only for signals co-propagating with the pump; this makes it possible to obtain very high single-pass gains, as reflections are not amplified. Likewise, the spontaneous emission associated with the amplification is emitted only in the direction of the pump; this can be exploited for making efficient amplified spontaneous emission (ASE) sources.

Compatibility with all-fiber devices

Silica-based fibers, and some others, can be fusion-spliced to common optical fibers and can thus be incorporated into assemblies consisting of other fiber components or fiber-pigtailed components. Such all-fiber devices benefit from increased stability compared with systems having discrete bulk-optic components.

High-power capability

Single-mode fiber lasers can now generate average output powers in excess of 1 kW. This indicates that, if needed, fiber OPAs could in principle also operate with these high pump powers. While such powers are excessive for telecommunication applications, they would be well suited for wavelength conversion, which could generate several hundred watts of average power at new wavelengths.

Distributed amplification

Just as in Raman amplification, parametric amplification can also be implemented along transmission fibers instead of between them.

Quantum effects

The fact that a signal photon and an idler photon are emitted simultaneously leads to the possibility of making sources of correlated photons; this could find applications in the emerging area of quantum communication.

These characteristics of fiber OPAs, taken alone or in combination, indicate that they could match or exceed the performance of other existing devices in various applications. While it was recognized early on that parametric amplification in optical fibers is a potentially important mechanism for amplifying optical waves for a variety of applications, its practical development was almost halted for 15 years, while EDFAs and RAs were being developed. The reason for this is that the considerable potential of fiber OPAs is difficult to exploit, for a variety of reasons, in particular: (i) the lack of fibers with a high nonlinearity coefficient γ; (ii) the need for phase matching, difficult to maintain because of longitudinal variations of the fiber ZDW λ_0; (iii) the lack of suitable pump sources, particularly for CW applications.

For these reasons, the early work with fiber OPAs was done with pulsed lasers, with peak powers of up to 1 kW. By using such high powers, it was possible to obtain a high gain in just a few meters of fiber. Also, a high pump power produces large amounts of self-phase modulation (SPM) and cross-phase modulation (XPM), which relax the phase-matching conditions and increase the gain bandwidth. Finally, with short fibers the effect of longitudinal variations in λ_0 is reduced. With these conditions, it is thus possible to obtain nearly ideal performance of fiber OPAs. Parametric amplification in optical fibers was first observed this way by Stolen in 1975 [1]. Lin *et al*. obtained high gain in a 50-m-long communication fiber, sufficient to yield substantial ASE at the wavelengths of peak gain [2]. Similar work was done by Washio *et al.* [3] and by Dianov *et al*. [4].

In the early work, the emphasis was on achieving wavelength conversion between two widely spaced but fairly narrow spectral regions. The location of these regions with respect to the pump was adjusted by one of two means. In communication fibers, by tuning the pump wavelength λ_p in the vicinity of λ_0, it is possible to obtain gain regions located several hundred nanometers away from λ_0; these can be moved by tuning λ_p.

This is the method used in [2] and [3]. Alternatively, by using a polarization-maintaining fiber (PMF) with a large birefringence, it is also possible to obtain large wavelength shifts, owing to the role of birefringence in phase matching when the pump and signal have orthogonal polarizations. In this case tuning is more difficult, because it must be accomplished by changing the birefringence; this can be done by applying a stress perpendicular to the fiber [5] or by heating the fiber [6]. By this method, gain regions around 904 nm and 1292 nm were obtained with a pump at 1060 nm [5]. In spite of these early accomplishments, in the mid-1980s fiber OPAs did not compare well with RAs [7]. In addition, with the advent of the enormously successful EDFAs in the late 1980s, there seemed to be little need for developing an alternate type of optical amplifier and, as a result, research activity on fiber OPAs waned.

Nevertheless, the ability of phase-sensitive fiber OPAs to achieve a zero dB noise figure, as well as to generate squeezed light, sparked activity on this type of OPA. In 1990, Marhic *et al*. and Bergman *et al*. simultaneously reported the first demonstrations of phase-sensitive amplification in nonlinear Sagnac interferometers [8, 9]. This work was followed by some activity on phase-sensitive fiber OPAs, but their delicate nature made application to mainstream communications problematic.

In 1996 Marhic *et al*. reconsidered phase-insensitive fiber parametric amplification and showed that by tuning λ_p near λ_0 it is in principle possible to obtain gain regions that are tens and even hundreds of nanometers wide, even with commonly available communication fibers and reasonable pump powers (of the order of 1 W) [10]. Such bandwidths exceeded those of the EDFAs and RAs that were currently used in optical communication, and this indicated that fiber OPAs could play an important role as amplifiers in future optical communication systems. Spurred in part by these prospects, as well as by steady advances in the required components, the development of fiber OPAs was resumed a few years ago and is now intensifying.

An important factor in this recent activity has been the fabrication of fibers specifically designed to have a high γ (of the order of 20 W^{-1} km^{-1}, i.e. about ten times larger than that for typical communication fibers), as well as λ_0 values around 1.55 μm. The abbreviations HNLF (highly nonlinear fiber) or HNL-DSF (highly nonlinear dispersion-shifted fiber) are often used to refer to such fibers. Having $\lambda_0 \approx 1.55$ μm is very important from a practical standpoint, as it allows the user to obtain good phase matching over wide regions in the vicinity of 1550 nm, which is currently one of the most important wavelengths in optical communication. The first highly nonlinear fibers of this type were made in 1995 by Holmes *et al*. at BT Laboratories in the UK [11]; several other manufacturers now make similar fibers. These fibers have made it possible to bring the performance of fiber OPAs much closer to their theoretical potential, particularly in terms of bandwidth.

Experiments in this wavelength range have also been greatly facilitated by the availability of components developed for optical communication systems, such as tunable lasers and EDFAs, which can be used to generate the narrow-linewidth high-power pumps required for fiber OPAs. In particular, the output power of EDFAs has been climbing steadily in recent years, while their prices have remained stable: today one can purchase a 3 W EDFA for the price of a 100 mW EDFA about five years ago. This trend has allowed experimentalists to upgrade their equipment and move to steadily higher pump powers, which are very important for developing high-performance fiber OPAs.

In summary, with the increasing availability of suitable equipment, significant progress has been made in recent years towards the realization of the potential of fiber OPAs. Important demonstrations have been the following.

- **A pulsed bandwidth of up to 400 nm** Fiber OPAs with pulsed gain bandwidths ranging from 200 nm to 400 nm have been demonstrated in recent years [12, 13]. This work used a pulsed pump, with about 10 W peak power, which is too high for optical communication applications.
- **A CW bandwidth of 100 nm** A 100 nm bandwidth was demonstrated with a single-pump OPA using a 4 W pump [14]. The CW operation means that such devices are compatible with applications in optical communication.
- **A continuous gain of 70 dB** [15] This was accomplished with a 2 W pump and shows that, if necessary, fiber OPAs can exhibit gains as large or larger than can be obtained with other types of fiber amplifiers, such as EDFAs or Raman amplifiers. Similar gains have also been obtained with a pulsed pump [13].
- **A noise figure of 3.7 dB** [16] This result is important because it demonstrates that fiber OPAs can have noise figures similar to those of EDFAs and Raman amplifiers.
- **Polarization-independent operation** [17, 18] As is the case for many other optical communication components and subsystems, it is desirable to have polarization independence for fiber OPAs. This means that the gain should be independent of the state of polarization (SOP) of the incident signal. Fiber OPAs (like Raman amplifiers) in their simplest forms are strongly polarization dependent. However, by using techniques such as polarization diversity [17, 18], it is possible greatly to reduce the polarization dependence.
- **High-speed optical processing applications** Fiber OPAs have been used to demonstrate a large variety of high-speed optical-processing applications, such as wavelength conversion, the demultiplexing of time-division-multiplexed (TDM) signals, optical sampling, signal regeneration, multiband processing, etc.
- **Distributed parametric amplification** Amplification in typical transmission fibers, 75 km long, has recently been achieved [19]. Also, phase-sensitive amplification was obtained in a 60-km-long fiber [20]. These results indicate that potentially parametric amplification in transmission fibers could compete with distributed Raman amplification and could eventually provide transmision links having nearly ideal noise properties.

With the demonstration of these features, all of which are necessary for practical applications, it is now becoming apparent that fiber OPAs may begin to find applications in optical communication, as well as in other fields. Thus it was felt that this was an opportune time for a book on the subject, which would gather much of the knowledge on the subject in one place as well as highlight some of the remaining challenges. Such a book could be of interest to engineers and researchers in related areas, graduate students involved in research on fiber devices and communication systems, etc.

In this book we present the basic types of fiber OPA, review the theory of their operation, present the experimental state of the art, and conclude with speculations about possible future directions for the field. In Chapter 2 we review the main properties of single-mode fibers, as is necessary for an understanding of fiber OPAs. In Chapter 3 we present the main analytic scalar solutions known in the field: these range from simple exponential solutions, when loss and pump depletion are ignored, to various types of special functions when such effects are introduced. The motivation for treating analytic solutions in such detail is based on the belief that they are essential tools for the interpretation of numerical simulations and can provide results quickly where they are directly applicable. In Chapter 4 we extend the formulation to the case where the waves are in arbitrary SOPs and we see how to reuse the results of Chapter 3, with suitable modifications. In Chapter 5 we introduce fiber dispersion and investigate how it governs the shape of the gain spectra. We study in detail the limits of negligible pump depletion and strong pump depletion and see how to optimize spectrum shapes for various applications. In Chapter 6 we discuss the nonlinear Schrödinger equation (NLSE), which is an important tool for studying field propagation when closed-form solutions cannot be used. We present the results of numerical simulations obtained by the split-step Fourier method (SSFM) for realistic fibers with longitudinal variations in λ_0 and in residual birefringence. In Chapter 7 we consider the case where the pump is pulsed. We show how one can use quasi-steady-state solutions when the time variations are relatively slow and the SSFM when they are fast. In Chapter 8 we explain how a fiber optical parametric oscillator (OPO) is made from a fiber OPA by adding optical feedback. We study important aspects such as the oscillation threshold, output power, and conversion efficiency. In Chapter 9 we present in detail some quantum-mechanical aspects of fiber OPAs. Starting from first principles we derive the theoretical 3 dB limit for the NF of fiber OPAs used either as amplifiers or as wavelength converters; we also consider the case of degenerate fiber OPAs, which have a 0 dB NF limit. In Chapter 10 we consider the requirements for some key aspects of the pumps of fiber OPAs, specifically power, linewidth, and amplitude stability. We investigate in detail the impact on OPA performance of some of these aspects, including the conversion of pump frequency or intensity modulation into signal intensity fluctuations and hence NF degradation. In Chapter 11 we present the results of experiments that have been performed to verify some fundamental properties of fiber OPAs, including the maximum gain, the gain bandwidth, and the noise figure. In Chapter 12 we discuss the potential application of fiber OPAs to various areas of optical technology, including optical communication, high-speed optical signal processing, quantum communication, and high-power wavelength conversion. In each area we present recent results obtained by various research groups. In Chapter 13 an aspect of fiber OPAs that is very important for fiber communication, namely crosstalk between signals in systems using wavelength-division multiplexing (WDM), is treated. We investigate the role of key parameters such as dispersion, the number of pumps, etc. and discuss strategies for minimizing this crosstalk. In Chapter 14 we present the topic of distributed parametric amplification (DPA). We treat it separately because this application involves amplification in a long communication fiber rather than amplification in a discrete device placed between such fibers, as in Chapter 12. Finally in Chapter 15 we put forward possible research and development areas in which activity could be helpful for realizing the full potential of fiber OPAs.

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2 Properties of single-mode optical fibers

While parametric interactions between different transverse modes are possible in multimode fibers [1], most of the recent work on fiber OPAs has been done with single-mode fibers and there are good reasons for believing that they will continue to be the most important medium for the foreseeable future. For this reason, in the rest of the book we will deal almost exclusively with single-mode propagation and in this chapter will concentrate exclusively on the properties of single-mode fibers that are essential to the understanding of fiber OPAs.

A fiber supports the propagation of a single mode when the light wavelength is in a certain range. On the long-wavelength side, a symmetric fiber can in principle support propagation at any such wavelength. In practice, however, losses due to material absorption or bends will make propagation at long wavelengths increasingly difficult. On the short-wavelength side, the fundamental mode can also propagate at any wavelength; however, below the cutoff wavelength λ_{co} a second mode can also propagate. When this occurs, coupling between the two modes (induced by bends) results in reduced power in the fundamental mode and therefore an increase in loss. In addition, the material may also exhibit increased loss at short wavelengths. Fibers designed to operate over a particular range of wavelengths are optimized by taking into account these two high-loss regions.

2.1 Mode profile

The fundamental mode profile in single-mode fibers is generally well approximated by a circularly symmetric mode with a Gaussian profile. Thus the local irradiance (power per unit area) $I(r)$ is well described by

$$I(r) = I_0 \exp\left(-\frac{2r^2}{w^2}\right), \tag{2.1}$$

where r is the radial distance from the fiber axis and r_0 is the distance at which I drops to $1/e^2$ of its on-axis value, I_0. The quantity $2w$ is known as the mode field diameter (MFD).

The total power P carried by the mode is given by

$$P = \int_0^{2\pi} d\theta \int_0^{\infty} I(r) r\,dr = \pi w^2 I_0/2, \tag{2.2}$$

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where θ is the angle around the z-axis; P is the same as that for a beam of uniform irradiance I_0 and radius w.

2.2 Loss

All fibers attenuate the power of waves passing through them. There are several possible causes for this attenuation: Rayleigh scattering by sub-wavelength density fluctuations; scattering from the roughness of the core–cladding interface; scattering from the domain walls in polycrystalline materials; absorption by dopants or impurities; multiphonon absorption by lattice vibrations at long wavelengths.

At a particular wavelength the power attenuation is characterized by an attenuation constant α. If $P(z)$ denotes the power of the wave at a distance z along the fiber, its evolution is governed by the differential equation

$$\frac{dP}{dz} = -\alpha z, \tag{2.3}$$

with solution

$$P(z) = P(0)\exp(-\alpha z), \tag{2.4}$$

indicating an exponential decay. If SI units are used in Eq. (2.4), α is in nepers m^{-1}. In practice it is more common to use decibels (dB) than nepers. Then, if α' denotes the attenuation constant in dB m^{-1}, we have, approximately, $\alpha' = 4.3\alpha$. The power $P(z)$ can be written alternatively as

$$P(z) = P(0) \times 10^{-\alpha' z/10}. \tag{2.5}$$

Fiber attenuation always depends on wavelength, and the variation can be quite complicated over wide wavelength ranges. For example silica, the most transparent fiber to date, exhibits an attenuation as low as 0.15 dB km^{-1} at 1550 nm but the value is much higher above 2 μm and below 200 nm.

2.3 Propagation constant and dispersion

Let us consider for now an ideal lossless fiber. If a monochromatic wave with frequency ν (angular frequency $\omega = 2\pi\nu$) propagates as a single mode along the fiber, the spatio-temporal dependences of all its field components are harmonic functions of the distance along the fiber z and the time t. For example, the dominant electric field component can be written as

$$E(z,t) = E(0,0)\exp[i(\beta z - \omega t)], \tag{2.6}$$

where $E(0,0)$ is a complex phasor representing the initial amplitude and phase of the wave. The real electric field is $\mathrm{Re}\{E(z,t)\}$.

The quantity β is the propagation constant or wavevector and is a function of frequency. From β one can calculate the effective index $n_{\mathrm{eff}} = \beta c/\omega$, the phase velocity