Supercontinuum generation in optical fibers

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Outline

• Short historical background on supercontinuum.
• Introduction to nonlinear effects involving in the process of supercontinuum generation.
• Some latest results on supercontinuum and its applications.
• Some results of the investigations in INAOE
• Conclusions
What is supercontinuum?

Supercontinuum generation is a process where laser light is converted to light with a very broad spectral bandwidth, whereas the spatial coherence remains high.

Lasers:
- Narrow range of frequencies
- Very bright

• Natural light:
- Wide frequency range
- Not very bright

• Supercontinuum light:
- Very bright
- White
First observation.

1-GW, 532 nm, 5 ps pulse
Frequency doubled
Nd:Glass mode-locked laser

Several filaments were formed in the sample and broad band light was detected at the sample output. Four wave mixing and self phase modulation were supposed to be responsible for the effect.

R.R. Alfano and S.L. Shapiro, 1970
Optical fiber vs bulk materials

Nonlinear effects $\sim L^*P/S$

Fiber is very effective nonlinear material !!!

$S \lesssim \text{Several mm}^2 \text{ in fibers}$

$L \propto S / \lambda$

$\lambda / S \propto L$
First experiment with fibers (1976)

In 1976 Lin and Stolen reported a new nanosecond source that produced continua with a bandwidth of 110-180 nm centered on 530 nm at output powers of around a kW [Appl. Phys. Lett., v.28, pp. 216 -218 (1976)].

The system used a 10-20 kW dye laser producing 10 ns pulses with 15-20 nm of bandwidth to pump a 19.5 m long, 7 μm core diameter silica fiber.
Super continuum in fibers is effective at anomalous dispersion.

Telcom fibers $\lambda > 1300$ nm

$\lambda = 1.5$ $\mu$m
Pulse width 14 ps

NaCl color center laser

First SC experiment in Photonic Crystal Fibers

The 75-cm section of microstructure fiber with the 1.7 µm diameter of nuclear. The dashed curve shows the spectrum of the initial 8-kW 100-fs pulse from Ti-sapphire laser.

SC in tapered fibers

Theoretical background
Spectrum of pulses

\[ \Delta f = \frac{A}{\Delta t} \]

\( A = 0.46 \) for Gaussian pulse
\( A = 0.32 \) for secant hyperbolic
if the pulse and spectrum width are measured as the Full Width at Half Maxima (FWHM).

At \( \Delta t = 1 \) ps   \( \Delta \lambda = 4 \) nm
\( (\lambda = 1550 \) nm)
Propagation of pulsos, phase velocity, group velocity

\[ v_g = \frac{d\omega}{d\beta} = \left( \frac{d\beta}{d\omega} \right)^{-1} = \frac{c}{\pi + \omega \frac{dn}{d\omega}} \]

\[ E(z, t) = A(z, t) e^{-i(\omega_0 t - \beta_0 z)} \]

\[ \phi = 0; \text{ se mueve con velocidad de fase} \]

\[ v_{ph} = \frac{\omega}{\beta} = \frac{c}{n} \]

\[ \beta = \frac{2\pi}{\lambda} = \frac{\omega}{c n} \]
Dispersion relation, group velocity dispersion

\[ \beta(\omega) = \beta(\omega_0) + \frac{\partial \beta}{\partial \omega} (\omega - \omega_0) + \frac{1}{2} \frac{\partial^2 \beta}{\partial \omega^2} (\omega - \omega_0)^2 + \ldots \]

An interval of frequencies in our process

\[ \beta_1 = \frac{\partial \beta}{\partial \omega} = \frac{1}{v_{gr}} \quad \beta_2 = \frac{\partial^2 \beta}{\partial \omega^2} = \frac{d(1/v_{gr})}{d\omega} \]

\[ \beta(\omega) = \beta_0 + \beta_1 (\omega - \omega_0) + \frac{\beta_2}{2} (\omega - \omega_0)^2 + \ldots \]

\[ \beta_2 > 0; \text{ normal dispersion} \]

(red light is faster than blue)

\[ \beta_2 < 0; \text{ anomalous dispersion} \]

(blue light is faster than red)

\[ \frac{\omega}{\beta} > 0; \quad \frac{\partial \omega}{\partial \beta} = 0; \quad v_{gr} = 0 \]

\[ \frac{\omega}{\beta} > 0; \quad \frac{\partial \omega}{\partial \beta} < 0; \quad v_{gr} < 0 \]

\[ \frac{\omega}{\beta} = \frac{\partial \omega}{\partial \beta} \quad v_{ph} = v_{gr} \]
Another definition of group velocity dispersion

Anomalous dispersions; D>0 ($\beta_2<0$)

$$t_1 - t_2 = D(\lambda_1 - \lambda_2)L$$

$$D = -\beta_2 \frac{2\pi c}{\lambda^2}$$
Super continuum in fibers is effective at anomalous dispersion. Telcom fibers $\lambda > 1300$ nm

$\lambda = 1.5 \, \mu m$
Pulse width 14 ps

Nonlinear index refraction

\[ n = n_0 + \tilde{n}_2 \frac{P}{A_{\text{eff}}} \]

\[ \tilde{n}_2 = 3 \cdot 10^{-20} \text{ m}^2 / \text{W} \]

At high power of light the refraction index is changed.

\[ \beta = \frac{\omega}{c} n = \frac{\omega}{c} \left( n_0 + \tilde{n}_2 \frac{P}{A_{\text{eff}}} \right) \]

\[ \Delta \beta_{NL} = \frac{\omega}{c} \tilde{n}_2 \frac{P}{A_{\text{eff}}} \]

At high power of light the wave number is changed; phase and group velocities are changed.
Equations for pulse propagation

\[
\frac{\partial A(z,t)}{\partial z} + \beta_1 \frac{\partial A(z,t)}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A(z,t)}{\partial t^2} + \ldots = i\Delta \beta_{NL} A
\]

\[
t' = t - \beta_1 z; \quad \text{Retarded time frame}
\]

\[
\frac{\partial A(z,t)}{\partial z} + \frac{i}{2} \beta_2 \frac{\partial^2 A(z,t)}{\partial t^2} = i\Delta \beta_{NL} A = i \frac{\omega}{c} \bar{n}_2 |A|^2 A
\]
Effects of nonlinearity ($n_2$) and group velocity dispersion ($\beta_2$)
Nonlinear chirp in the pulse at $\beta_2=0$

**Self Phase Modulation, SPM**

\[
E(z,t) = A_0 e^{i(\omega_0 t - \beta z)} = A_0 e^{i(\omega_0 t - (\beta_0 + \Delta \beta) z)} = A_0 e^{i \varphi(t)}
\]

\[
\omega = \frac{d\varphi(t)}{dt} = \omega_0 - \frac{\omega}{c} \tilde{n}_2 \frac{1}{A_{\text{eff}}} \frac{dP(t)}{dt}
\]

**tailing edge,** \(dP/dt < 0\)

**leading edge,** \(dP/dt > 0\)

\(\omega > \omega_0\)

\(\omega < \omega_0\)
Broadening of the spectrum because of chirp

1 ps pulse; 20 m fiber; $D=0$
Low power pulse propagation in fiber; 1-W power pulse; D = 18 ps/nm-km
A 100 W power pulse propagation in fiber with anomalous dispersion; $D=18 \text{ ps/ nm-km}$
Soliton

\[ E(t) = \sec h(t / T_0) = \frac{2}{e^{t/T_0} + e^{-t/T_0}} \]

dispersion must be anomalous

\[ \frac{P_0}{A_{eff}} \frac{T_0^2}{|\beta_2|} \tilde{n}_2 \kappa_0 = 1 \]

The condition for the pulse to be soliton

The shape of soliton is not changed in propagation,

1-ps FWHM soliton

P = 44 W at D = 18 ps/nm-km
Propagation of a 20-W 50-ps pulse through the fiber with anomalous dispersion
Modulation instability (MI) at anomalous dispersion causes the amplification of fluctuation and pulse breakup

\[ amplification = e^{gL} \]

\[ g_{\text{max}} = 2\gamma P_0 \]

\[ \omega_{\text{max}} = \pm \left( \frac{2\gamma p_0}{|\beta_2|} \right)^{1/2} \]
Propagation of a 20-W, 50-ps pulse through the 200-m fiber with normal dispersion

Pulse

Spectrum
Behavior of the pulse in the fiber is affected drastically by the sign of the dispersion.

$D > 0$: normal dispersion
$D < 0$: anomalous dispersion

Small anomalous dispersion is favorable for supercontinuum !!!
Silica Glass Optical Fibers, dispersion tuning

- Protective polymer sheath
- Silica cladding $n \sim 1.45$
- "high" index doped-silica core $n \sim 1.46$
- "LP$_{01}$" confined mode field diameter $\sim 8\mu m$
- More complex profiles to tune dispersion

Possibilities of dispersion tuning are restricted by properties of glasses
Calculated dispersion for small core fiber

D>0, anomalous dispersion

2 μm core diameter; Δn=0.3

1 μm core diameter; Δn=0.1

From J. K. Ranka, R. S. Windeler, A. J. Stentz, 2000
Photonic Crystal Fiber (PCF)
Microstructured Fiber (MSF)

Class 1

Holes
Glass

Large mode area (LMA)
High Nonlinear (HNL)
High Numerical Aperture (HNA)

INAOE, 27/04/2011
Some examples of PCF from Universidad de Valencia

25 μm

5 μm

35 μm

INAOE, 27/04/2011
First Supercontinuum Experiment in Photonic crystal fibers

Squares – measured PCF
Circles – standard fiber

Ti:sapphire 1.6 kW, 100 fs pulses were used for pump

From J. K. Ranka, R. S. Windeler, A. J. Stentz, 2000
Dispersion for tapered fiber and supercontinuum generation


Ti:sapphire 100 fs pulses were used for pump
Stimulated Raman scattering

\[ P_S(z) = P_S(0) e^{g \frac{P_P}{A_{\text{eff}}} z} \]

\( g \) – Raman gain coefficient

New spectral lines shifted by appr. 12 THz to “red” may appear as a result of SRS
Raman self-frequency shift

\[ \frac{\partial A_p}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A_p}{\partial T^2} = i\gamma_p |A_p|^2 A_p \]

Equation for pulse propagation

\[ \frac{\partial A_p}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A_p}{\partial T^2} = i\gamma_p |A_p|^2 A_p + T_R \frac{\partial |A_p|^2}{\partial T} A_p \]

Raman term

\( T_R = 3 \text{ fs} \)

This part as pump

This part as Stokes

Spectrum of the 100 fs pulse

\[ \Delta \lambda \propto \frac{1}{T_0^4 L} \]

INAOE, 27/04/2011
Modulation instability starts pulse break and soliton formation. Solitons are shifted to the red by soliton self frequency shift.

\[ \frac{\partial A}{\partial z} + \frac{i \beta_2}{2} \frac{\partial^2 A}{\partial T^2} = i \gamma |A|^2 + T_R \frac{\partial |A|^2}{\partial T} \]

Basic equation for supercontinuum

The 20-W, 50-ps pulse after 1-km of fiber
Four wave mixing

\[ \omega_3 + \omega_4 = \omega_1 + \omega_2 \]
\[ \Delta k = k_3 + k_4 - (k_1 + k_2) = 0 \]
\[ \Delta k = \left( n_3 \omega_3 + n_4 \omega_4 - \left( n_1 \omega_1 + n_2 \omega_2 \right) \right) / c \]

The phase matching conditions is the principal problem to solve for effective FWM process.
The longer the fiber the less is tolerance to phase mismatching.
Preliminary summary of nonlinear effects involved to SC generation

Self phase modulation. It occurs at any dispersion; the pulse duration has to be shorter than 1 ps.

Soliton self frequency shift. Anomalous dispersion is required. It is effective for pulses shorter than 1 ps.

Modulation instability. It requires the anomalous dispersion; it is effective for long pulses including cw.

FWM. It is more effective for anomalous dispersion nearly the point of zero dispersion and for short fibers.
Part 2
Experimental results on SC
Preliminary summary of nonlinear effects involved to SC generation

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First observation

1-GW, 530 nm, 5 ps pulse

Several filaments were formed in the sample and broad band light was detected at the sample output. Four wave mixing and self phase modulation were supposed to be responsible for the effect.

R.R. Alfano and S.L. Shapiro, 1970
Soliton self-frequency shift in fibers

\[ \lambda = 1.5 \, \mu m \]

Pulse width 14 ps

NaCl color
Center laser

500-m fiber with anomalous dispersion

100-fs solitons were generated and soliton self frequency shift caused the spectrum broadening

First observation of super continuum in photonic a crystal fiber

Ti:sapphire 100 fs pulses were used for pump

J. K. Ranka, R. S. Windeler, A. J. Stentz, 2000
First supercontinuum observation in tapered fiber

Ti:sapphire 100 fs pulses were used for pump

Nanosecond supercontinuum in PCF

Experiments used a microchip laser producing 0.8-ns-duration pulses at 532 nm with an average output power of 5 mW.

ZDW = 770 nm

the extent of the spectral broadening is explained in terms of the interplay between Raman scattering and FWM.
Long pulses and cw supercontinuum

10 mW cw laser at 1065 nm was modulated and amplified by Yb amplifier. Pulse durations available are of 1 ns to several tens ns, or continuous wave (CW)

Yb modelocked laser as a source of pulses for SC generation

60kW peak - 8W average-power 2.2 ps duration and 40 MHz repetition rate pulses were generated at the output

A. B. Rulkov, M. Y. Vyatkin, V. Popov, J. R. Taylor, Optics Express 2005
The Yb source was spliced to PCF with zero dispersion at 1040nm, mode field diameter of 3.2μm and attenuation of less than 2dB/km.

A. B. Rulkov, M. Y. Vyatkin, S. V. Popov, J. R. Taylor, Optics Express 2005
SC in 1550 nm region is also investigated

Takashi Hori, Jun Takayanagi, Norihiko Nishizawa, and Toshio Goto, Optics Express, 2004
Possible configuration for SC generation - 1; direct pumping

Ju Han Lee and Kazuro Kikuchi, Optics Express, 4848 (2005)
Possible configuration for SC generation - 2; Er laser with high nonlinear (HNL) fiber in a cavity

Ju Han Lee and Kazuro Kikuchi, Optics Express, 4848 (2005)
Possible configuration for SC generation - 3; Raman laser with high nonlinear (HNL) fiber in a cavity.

Ju Han Lee and Kazuro Kikuchi, Optics Express, 4848 (2005)
PCF at 1550 nm pumping

High average power SC

Application of SC
Ultra high resolution optical coherence tomography (OCT) for bio-medical investigations

Traditional OCT is based on superluminescent diode light sources; resolution 10 – 15 µm

Broadband modelocked Ti:Al2O3 lasers have been demonstrated to extend the axial resolution to 1-5 µm in tissue. However these systems are expensive

All fiber SC generator can be a good choice.
Low coherence interferometry

Signal appears only if $L_1 = L_2$ within the coherence length
Special calculations were done to choose the PCF characteristics and obtain desirable SC spectrum.
Example of the tomography of skin

800-nm supercontinuum  1300-nm supercontinuum
All Fiber Source of Supercontinuum for Optical Tomography

Experimental Results Obtained with Al-fiber SC Source

Spectrum of the radiation

Human skin
Optical Frequency Measurements

Examples of two different optical frequency standards:
- 657 nm (456 THz) standard using laser-cooled Ca atoms;
- 282-nm (1064-THz) standard using a single trapped and laser-cooled Hg ion.

How to measure the frequency with high accuracy?

Laser mode frequency comb may be used for very exact measurements

The use of the laser

Beating between lines can be measured very accurate

\[ f_N = f_0 + Nf_{rep} \]

1 GHz
The measurement of \( f_0 \)

\[
f_N = f_0 + Nf_{rep}
\]

Second harmonic generation

\[
2f_N = 2f_0 + 2Nf_{rep}
\]

Broad band laser pulses are required

Supercontinuum
Laser system for precision frequency measurement

Investigations in INAOE

E.A.Kuzin, B. Ibarra-Escamilla, INAOE
R.Rojas-Laguna, University of Guanajuato
O.Pottiez, CIO
J.W.Haus, Dayton University
M.V.Andres, Valencia Spain
Two stage amplifier of pump pulses

Input from DFB laser

980-nm pump

circulator

1549-nm FBG

10-m EDF

15-m EDF

980-nm pump

1:99 coupler

Output

Monitor

Power, W

Time, ns

pulse current, mA

0 10 20 30 40

0

5

10

15

20

25

0 5 10 15 20 25

0 10 20 30 40

5 10 15 20 25

8 7 6 5 4
Development of the modulation instability. The 210-m long fiber.
Raman enhanced supercontinuum generation.
The 9.13-km long fiber, 18 pump power.
The F8L with the polarization splitter used for the output

Nonlinear dependence for transmitted pulses
The soliton transmission for different EDFA amplifications

The maximum transmission moves towards longer soliton durations as the amplification increases. The calculations were done for 40-m long fiber in the loop.
Basic configuration for investigation of pulse breakup

\[
\frac{\partial A}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} = i\gamma \left( |A|^2 A - T_R A \frac{\partial |A|^2}{\partial T} \right)
\]

![Diagram of basic configuration](image)

\begin{align*}
\text{Fiber 1} & \rightarrow \text{EDFA} \\
\text{Fiber 2} & \rightarrow \text{Optical Attenuator} \\
\text{Output Pulse} & \rightarrow \text{NOLM} \\
\text{Dispersive fiber} & \rightarrow \text{Twisted Fiber}
\end{align*}

![Plot of power vs. time with T=0.8 ps](image)
Pulses at the NOLM output and at the end of the 500-m dispersive fiber

Output of the NOLM

Output of the dissipative fiber
Experimental setup used for extraction of solitons
**Effect the amplification of EDFA-2**

Autocorrelation traces At the NOLM output

Transmission at different amplifications
Autocorrelation functions at the NOLM input and output

A red line shows an autocorrelation function of the pump pulse.

NOLM input

NOLM output

A red line shows an Sech² profile.

10 W pump

15 W pump

20 W pump
Autocorrelation functions at the NOLM output and the dispersive fiber output

The NOLM output

20-W input pulse was applied

The dispersive fiber output

Soliton power is estimated as 100 W, 5 times higher than the input pulse power. This value corresponds to theoretical estimations.
Conclusions

The SC can be generated using many source of light: fs lasers, ns lasers, cw laser. Extremely important is the choice of the fiber with appropriate group velocity dispersion preferably in the anomalous dispersion region. Generally the mechanisms responsible for SC generation look to be clear, however many details are still for understanding. First commercial applications appear in last years.