

Generiranje superkontinuumu u nelinearnom optičkom vlaknu

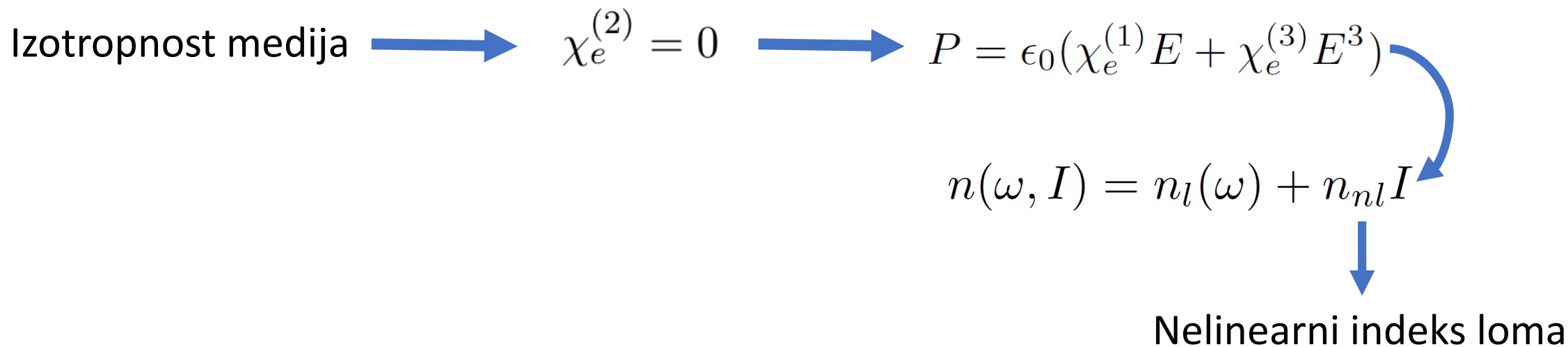
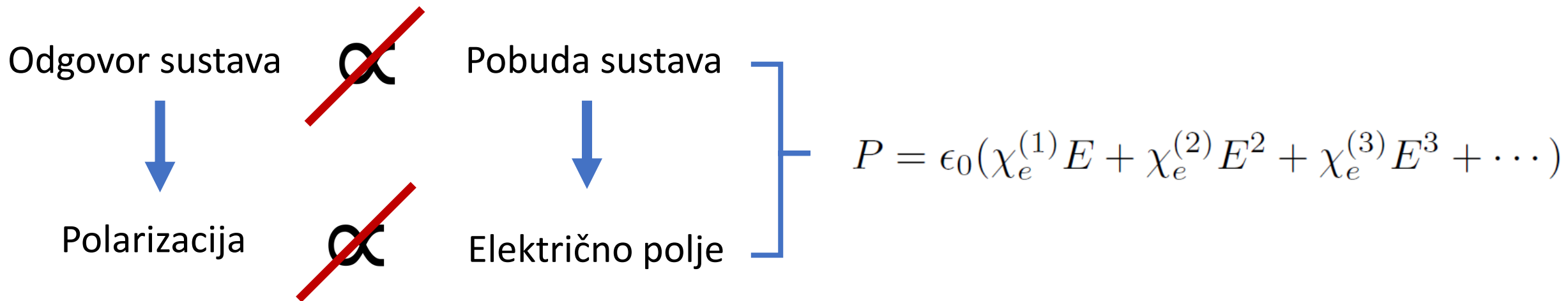
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Nelinearni odziv medija



Nelinearno optičko vlakno

Propagacija principom totalne refleksije

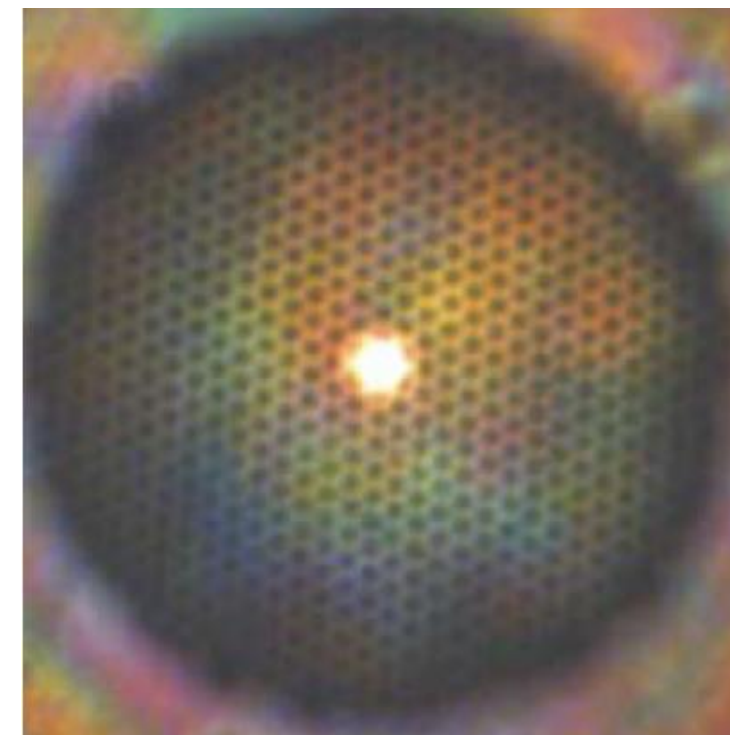
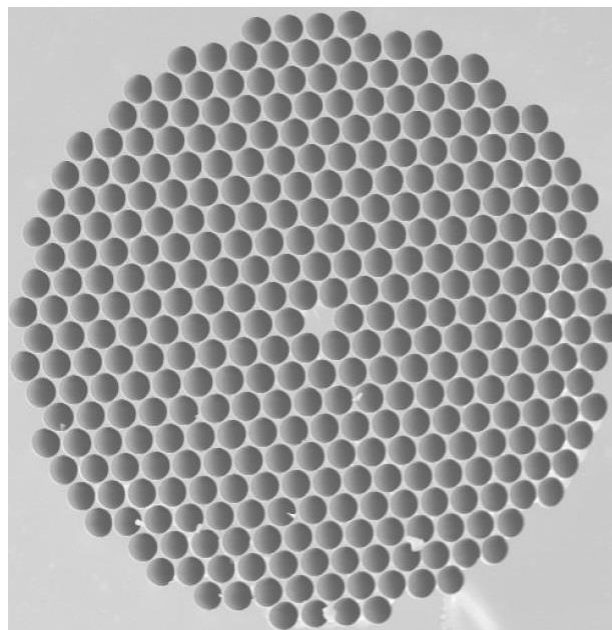
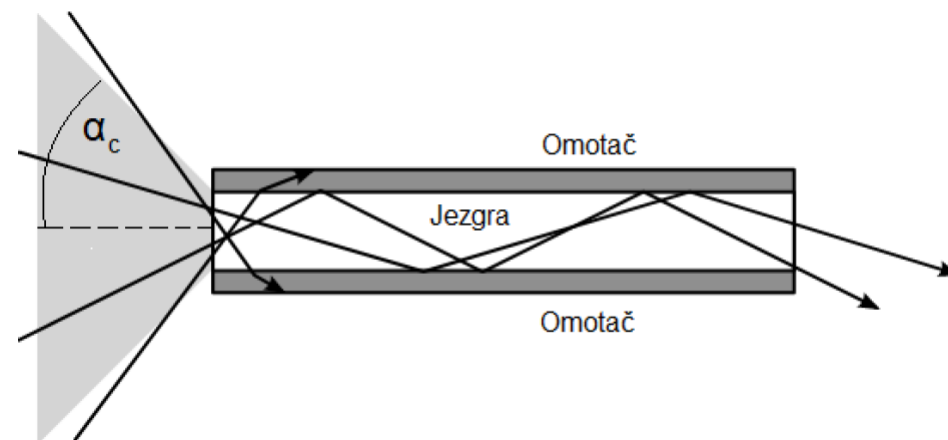
Numerička apertura = $NA = \sin(\alpha_c)$

Dvoindeksno fotoničko optičko vlakno

Jezgra (silika) + šupljine (zrak)

Šupljine \approx omotač niskog indeksa loma

Koeficijent nelinearnosti ovisi o promjeru jezgre, indeksu loma jezgre i rasporedu šupljina



Laserski pulsevi

Femtosekundni pulsevi

$\lambda=780\text{nm}$

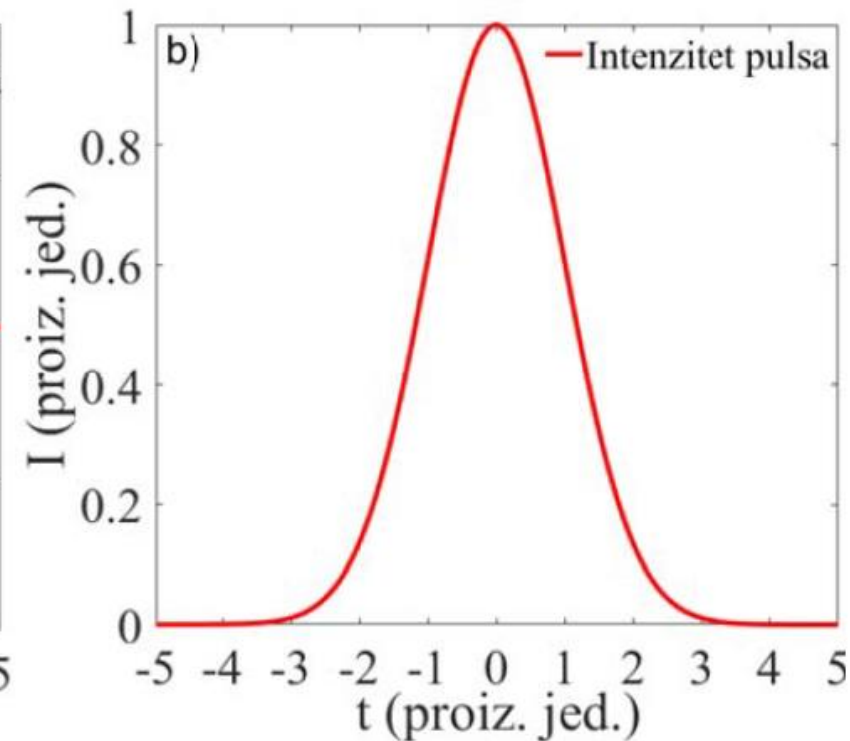
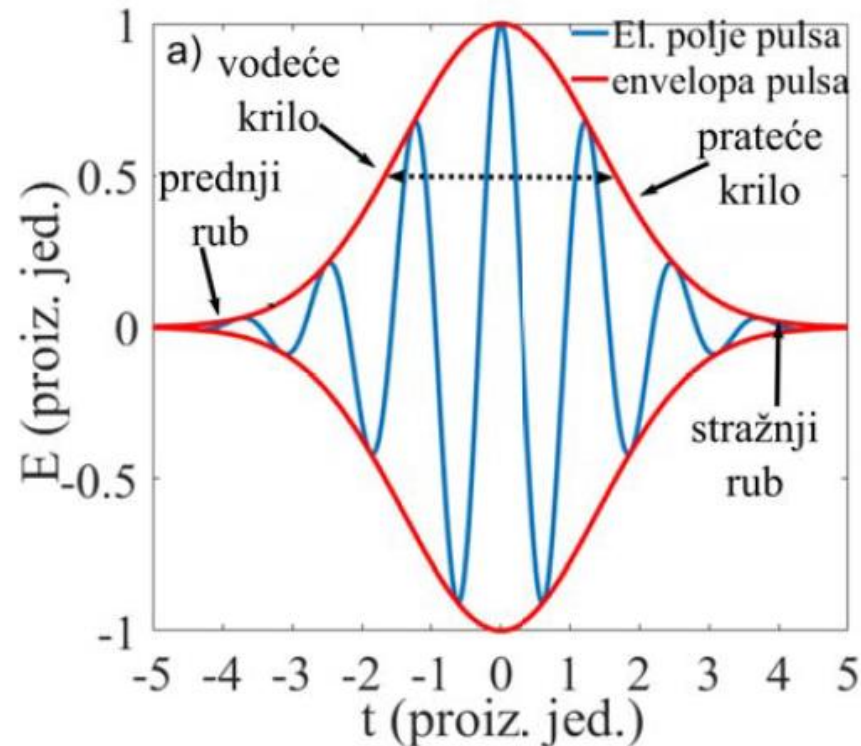
$$\mathbf{E} = A(t)e^{i(\omega_0 t + \phi(t) + \phi_0)} \hat{x}$$

Trenutna frekvencija:

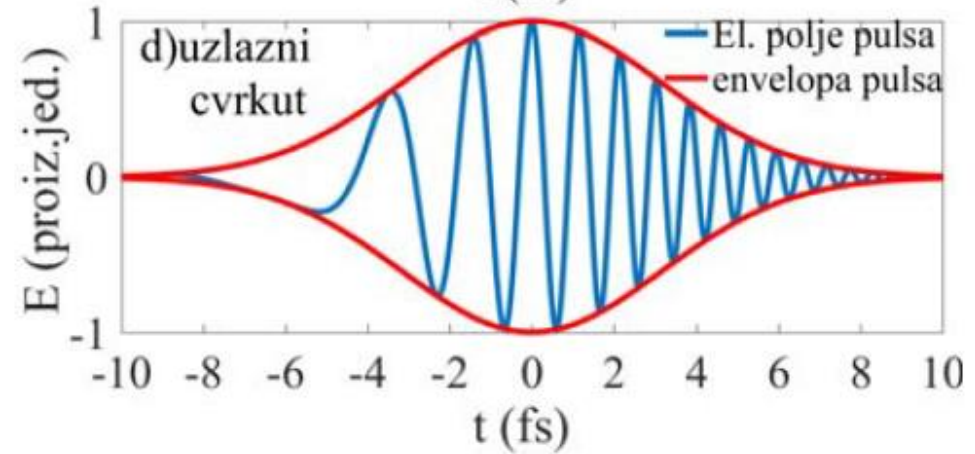
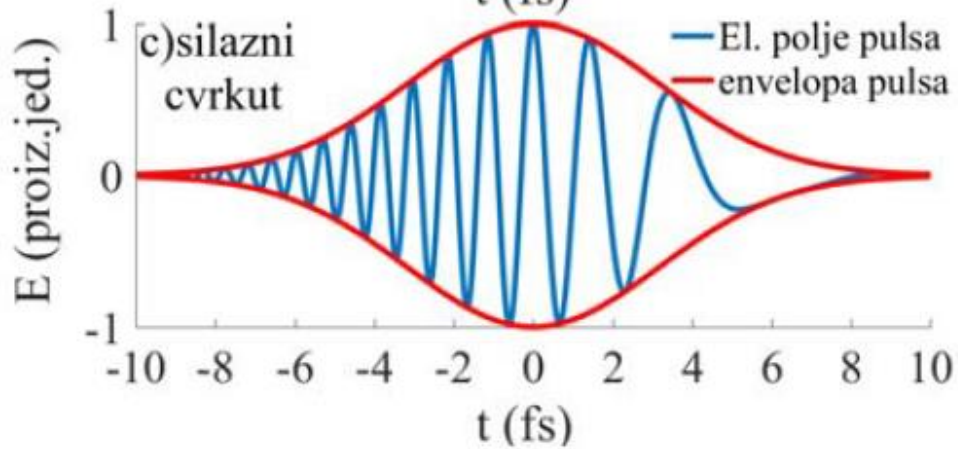
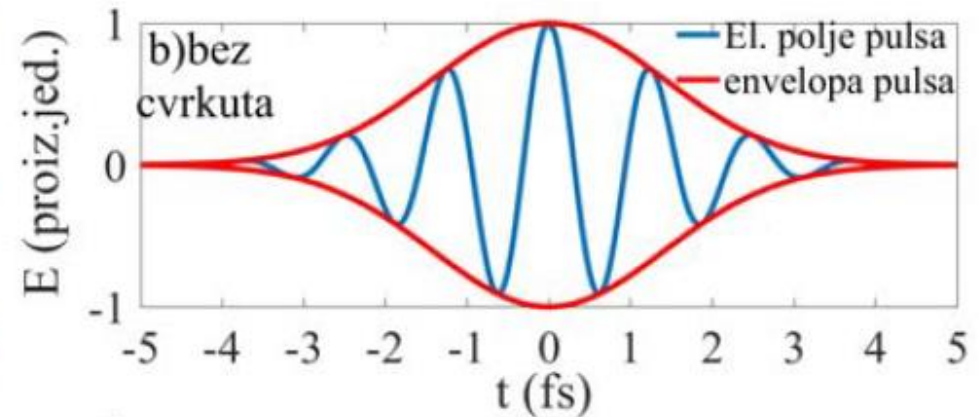
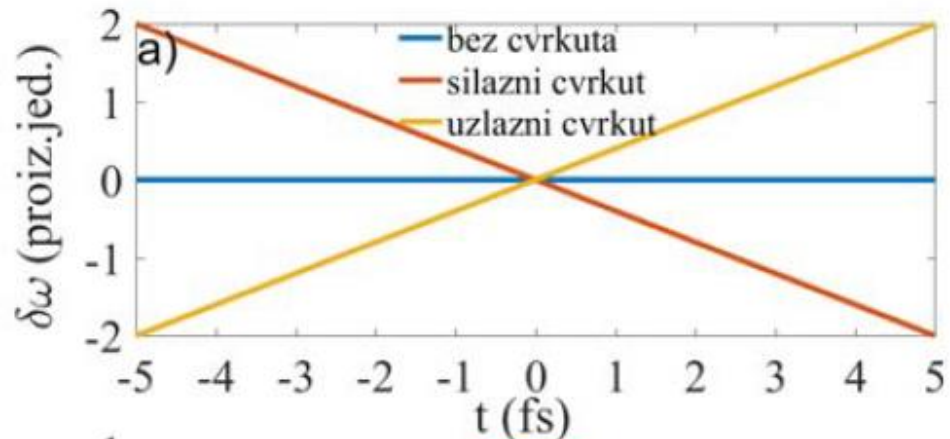
$$\omega(t) = \omega_0 + \frac{d\phi(t)}{dt}$$



Cvrkut pulsa



Cvrkut pulsa



Plave komponente brže
od crvenih



Crvene komponente brže
od plavih

Propagacija ultrakratkih laserskih pulseva u nelinearnom mediju

Aproksimacije:

- $$\beta(\omega) = \sum_{n=0}^{\infty} \frac{\beta_n}{n!} (\omega - \omega_0)^n \approx \beta_0 + \beta_1 \Delta\omega + \frac{1}{2} \beta_2 (\Delta\omega)^2 + \frac{1}{6} \beta_3 (\Delta\omega)^3$$
- Aproksimacija sporo varirajuće envelope
- $$P = \epsilon_0 (\chi_e^{(1)} E + \chi_e^{(3)} E^3)$$

Propagacija ultrakratkih laserskih pulseva u nelinearnom mediju

Generalizirana nelinearna Schrödingerova jednažba:

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial|u|^2}{\partial T} \right)$$

$$u = A\sqrt{S_{eff}} \longrightarrow |u|^2 = \text{snaga pulsa}$$

$$\gamma = \frac{3\omega_0 n_{nl}}{cS_{eff}} = \text{parametar nelinearnosti}$$

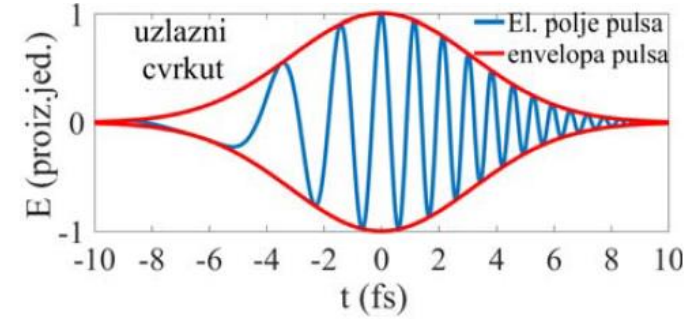
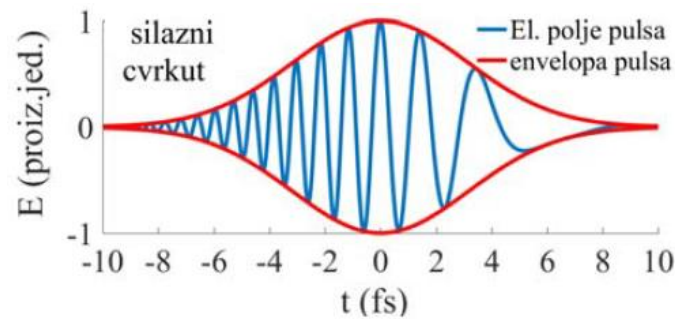
$$T = t - \beta_1 z = \text{vrijeme u sustavu pulsa}$$

Disperzija grupne brzine (GVD, Group Velocity Dispersion)

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial|u|^2}{\partial T} \right)$$

$\beta_2 > 0$ Normalni disperzivni režim

$\beta_2 < 0$ Anomalni disperzivni režim



$$\delta\omega(T) = \frac{d\phi(T)}{dT} = \text{sgn}(\beta_2) \frac{z/L_{GVD}}{1 + (z/L_{GVD})^2} \frac{T}{T_0}$$

→ Gaussijanski puls dobiva uzlazni ili silazni cvrkut

$$L_{GVD} = T_0^2 / |\beta_2|$$

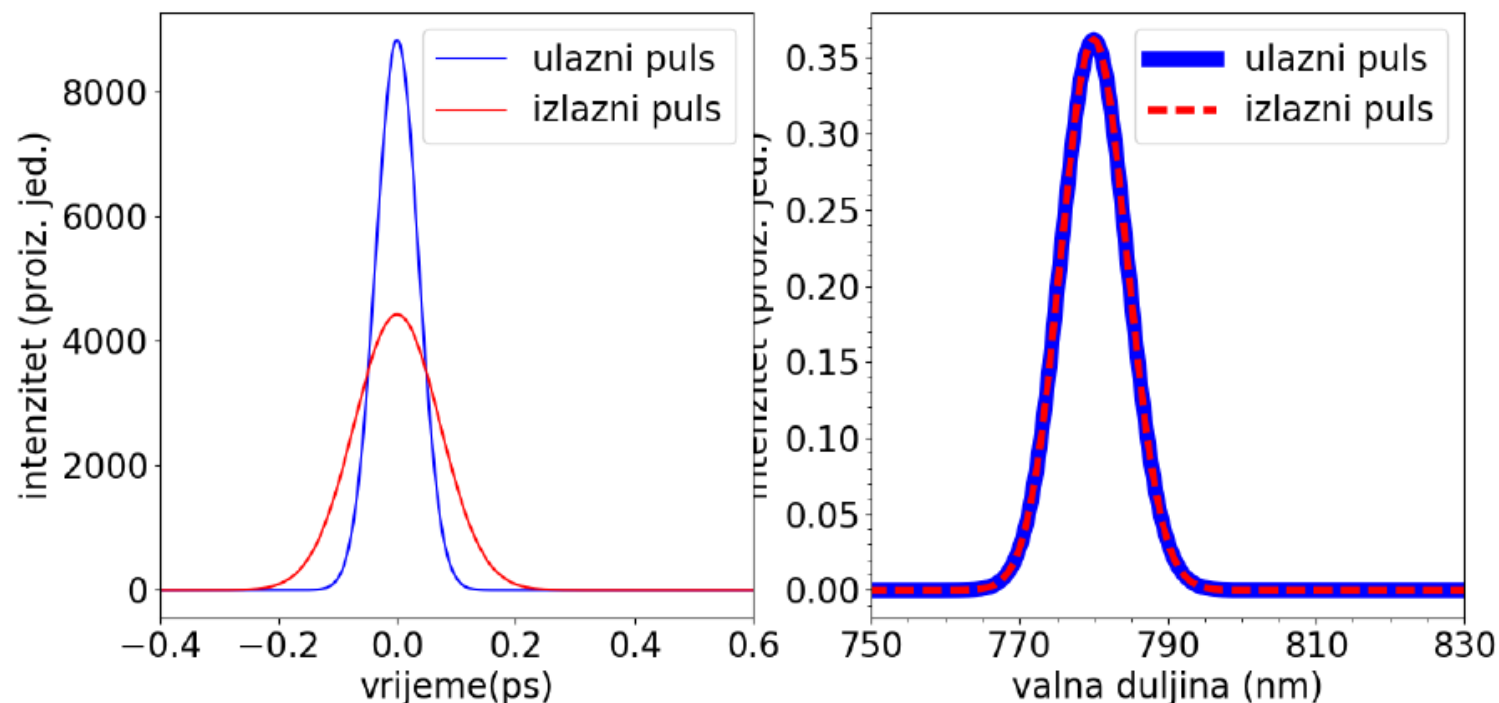
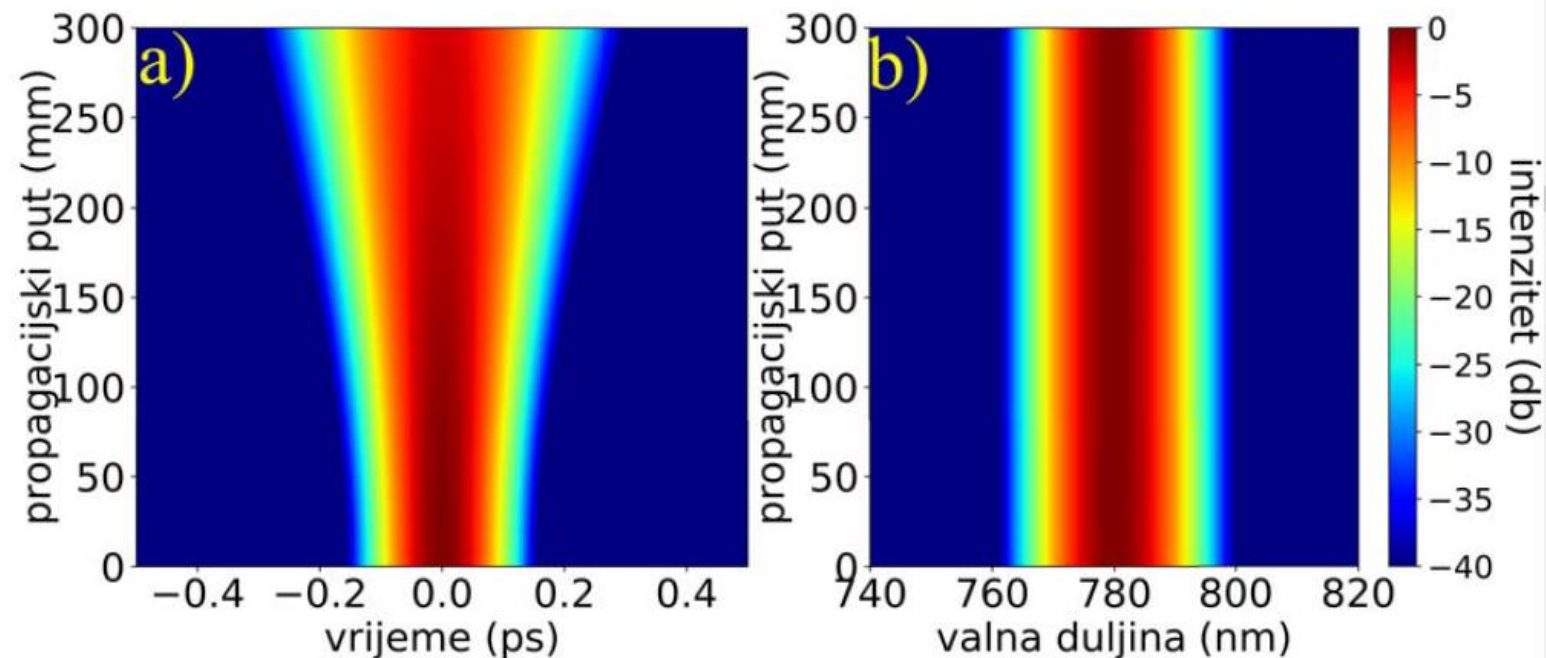
Rezultati simulacija:

$$\beta_2 = 15 \text{ps}^2/\text{km}$$

$$\beta_3 = 0$$

$$\gamma = 0$$

$z=300\text{mm}$



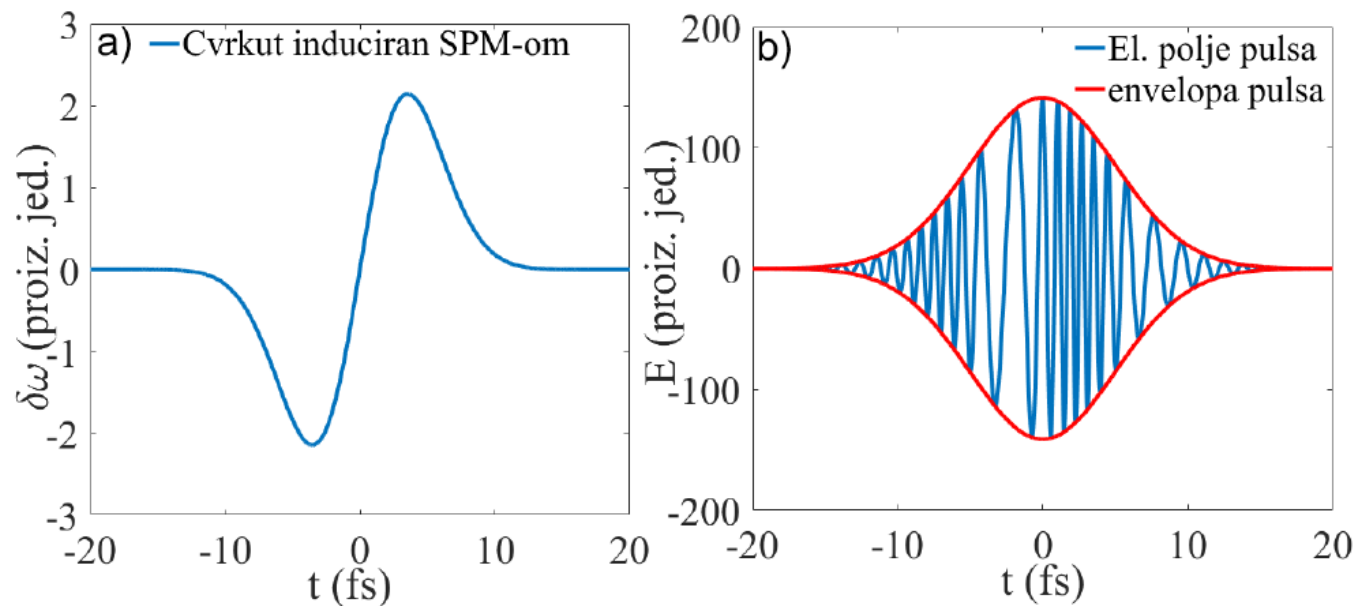
Samofazna modulacija (SPM, Self-Phase Modulation)

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial|u|^2}{\partial T} \right)$$

Gaussijanski puls dobiva cvrkut:

$$\delta\omega(T) = \frac{d\phi_{nl}}{dT} = \frac{2}{T_0} \frac{L}{L_{NL}} \frac{T}{T_0} e^{-\left(\frac{T}{T_0}\right)^2}$$

$$L_{NL} = 1/\gamma P_0$$



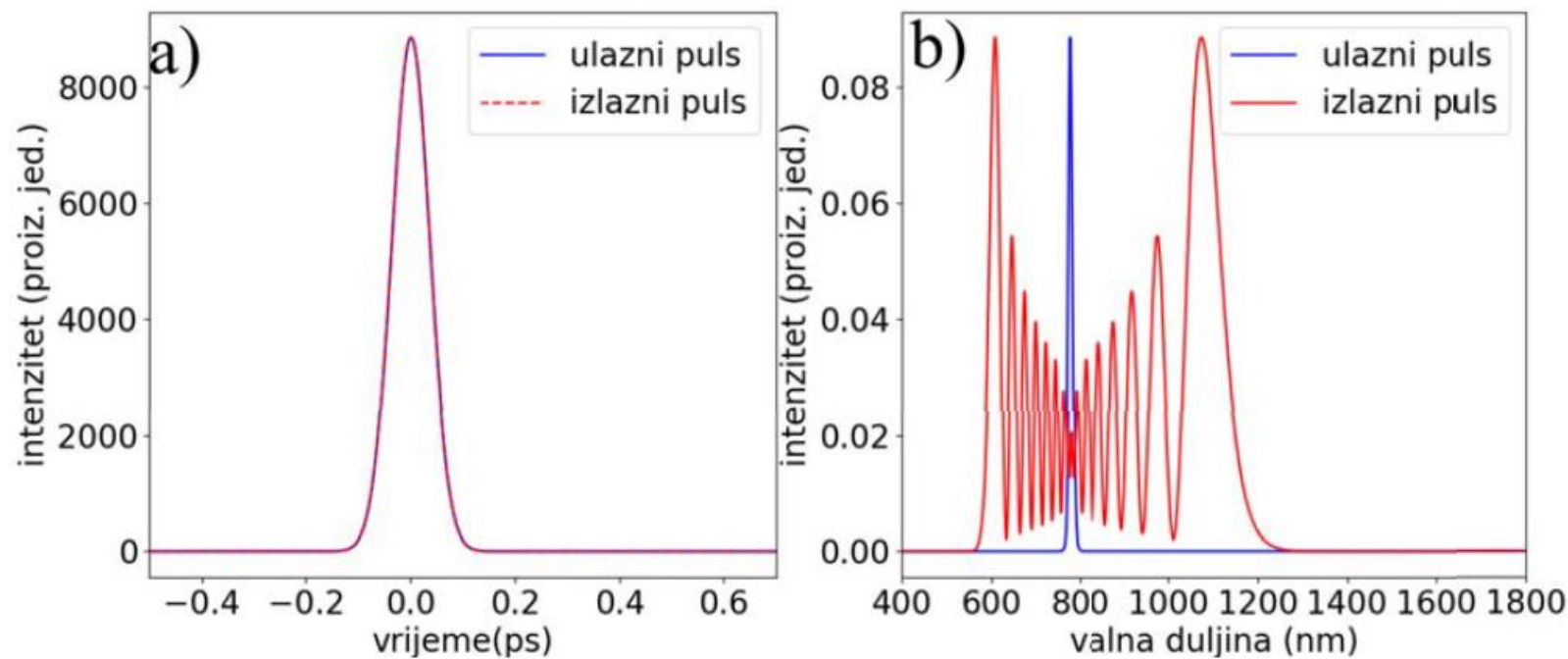
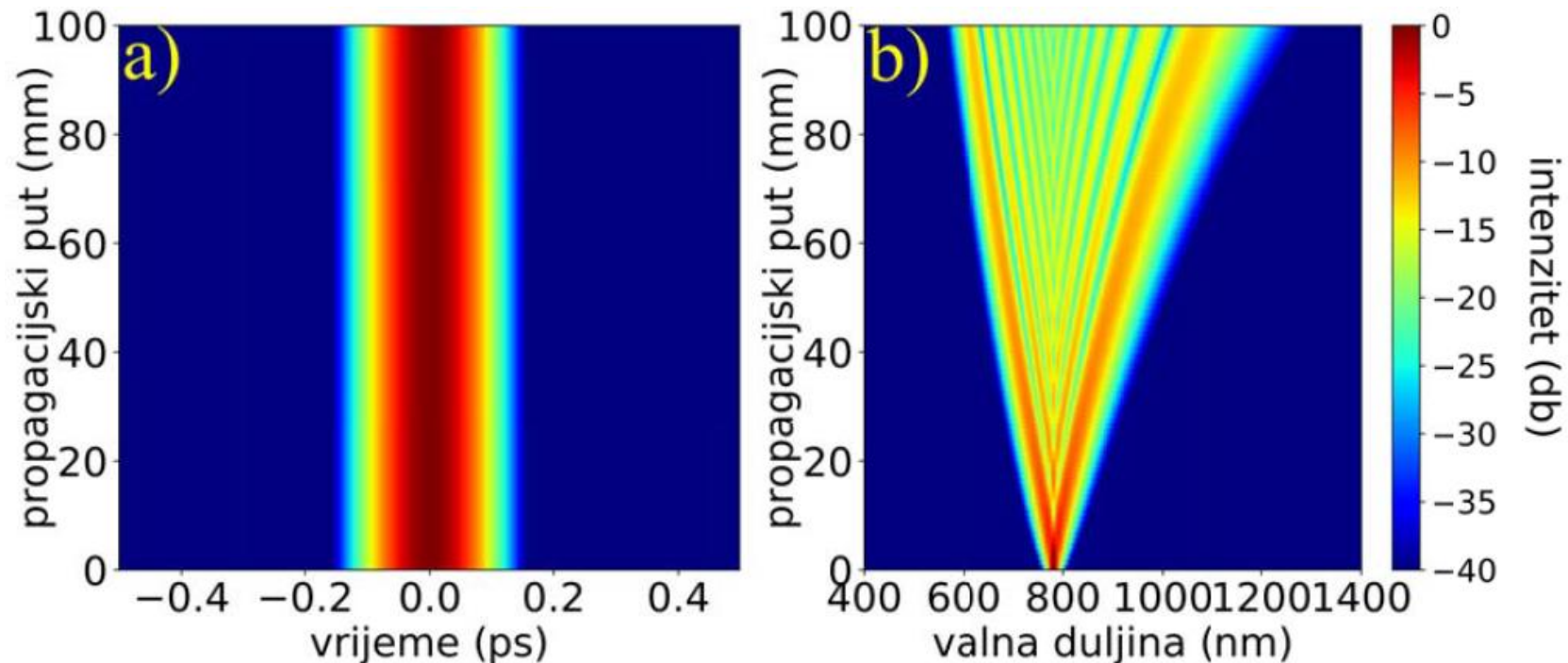
Rezultati simulacija:

$$\beta_2 = 0 \text{ ps}^2/\text{km}$$

$$\beta_3 = 0$$

$$\gamma = 50 \frac{1}{\text{Wkm}}$$

$z=10\text{cm}$



GVD + SPM

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial|u|^2}{\partial T} \right)$$

$$\frac{\partial U}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 U}{\partial T^2} = iN^2 |U|^2 U$$

$$u(z, t) = \sqrt{P_0} U(z, t)$$

P_0 = vršna snaga pulsa

$$N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

$$\beta_2 > 0$$

Lom optičkog
vala

$$\beta_2 < 0$$

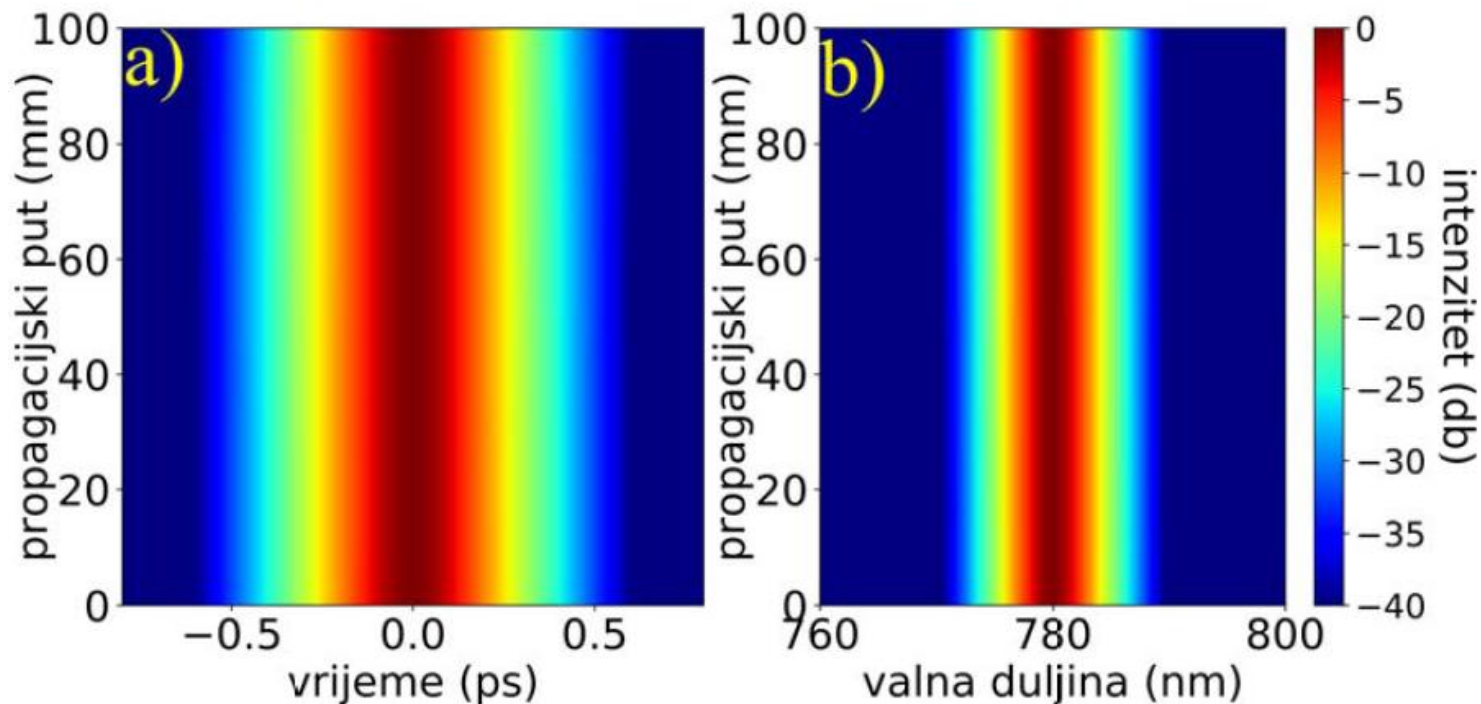
Stvaranje solitonskih
valova

Stvaranje solitonskih valova

$$\frac{\partial U}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 U}{\partial T^2} = i N^2 |U|^2 U$$

N=1

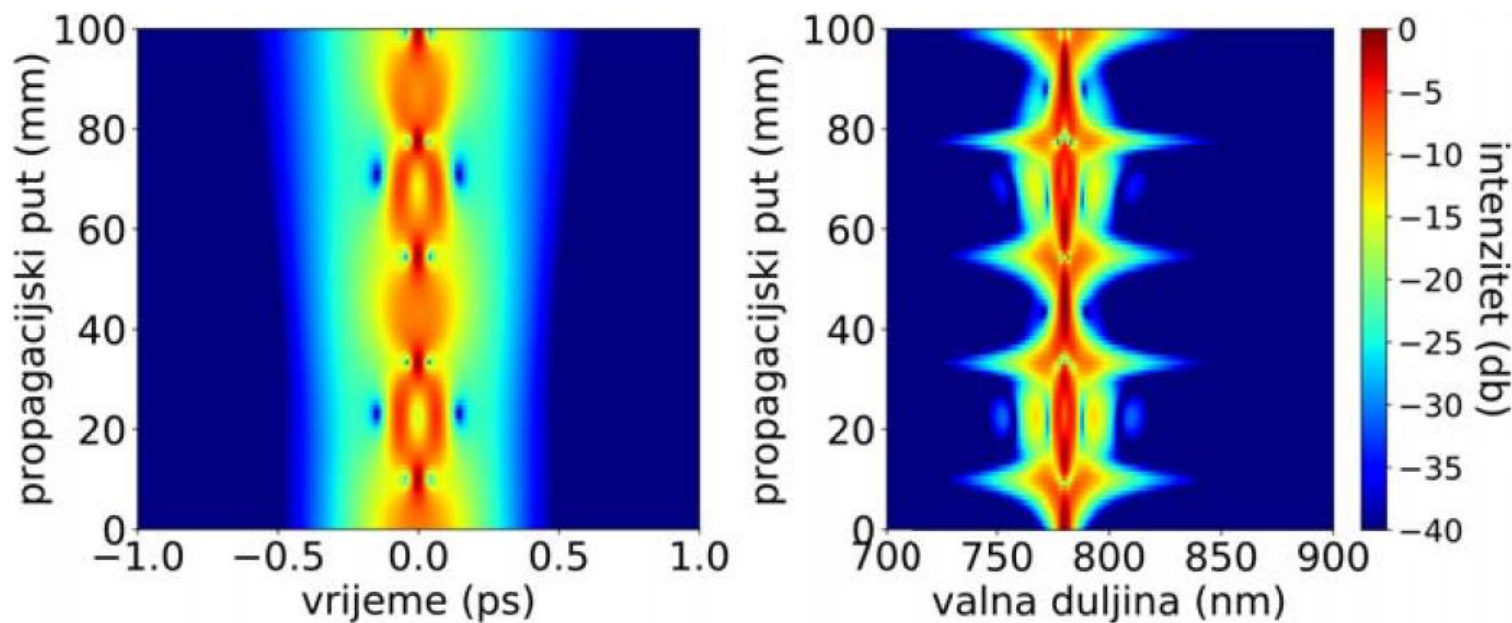
Soliton prvog reda
(fundamentalni soliton)



Ravnoteža disperzivnih i
nelinearnih efekata

N=3

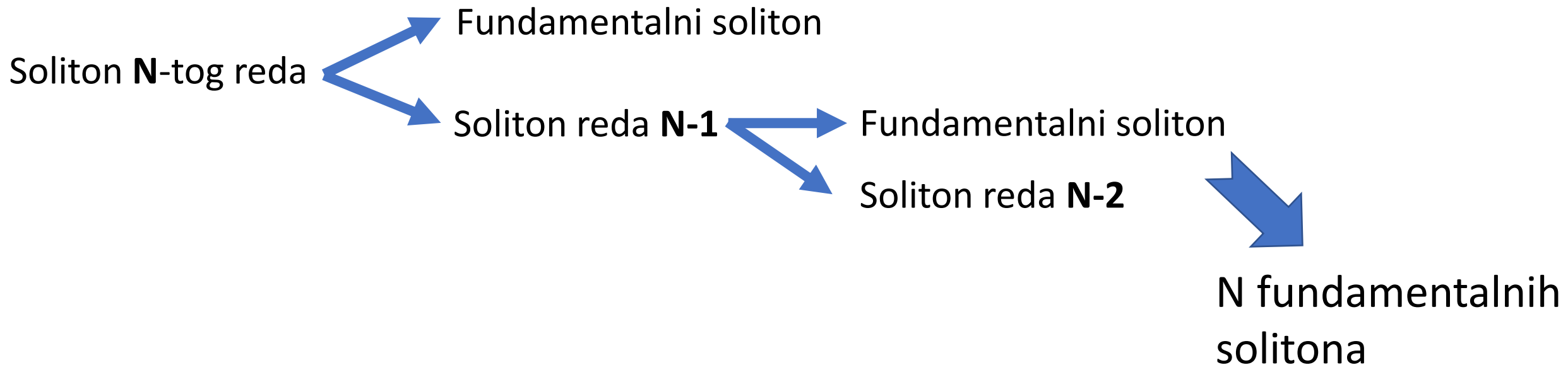
Soliton trećeg
reda



Disperzija trećeg reda (TOD, Third Order Dispersion)

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial |u|^2}{\partial T} \right)$$

Solitonska fisija:



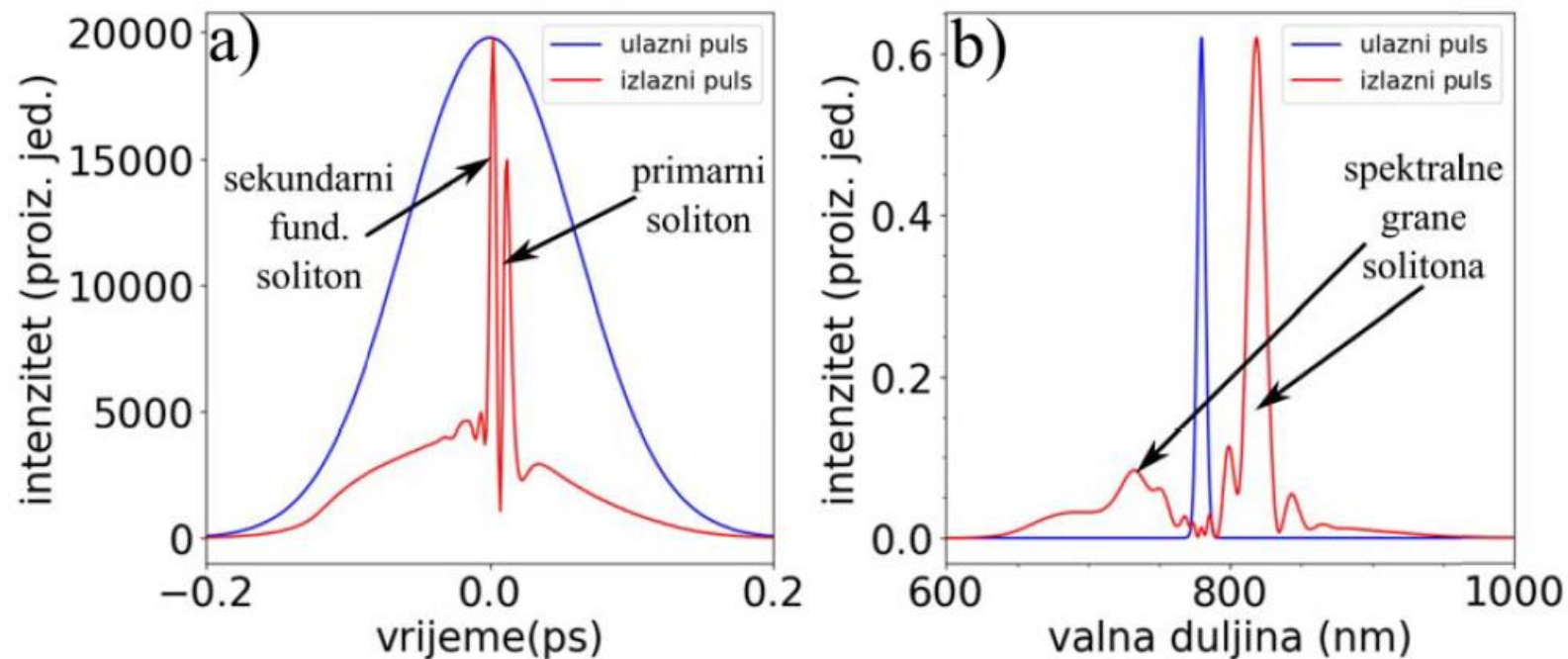
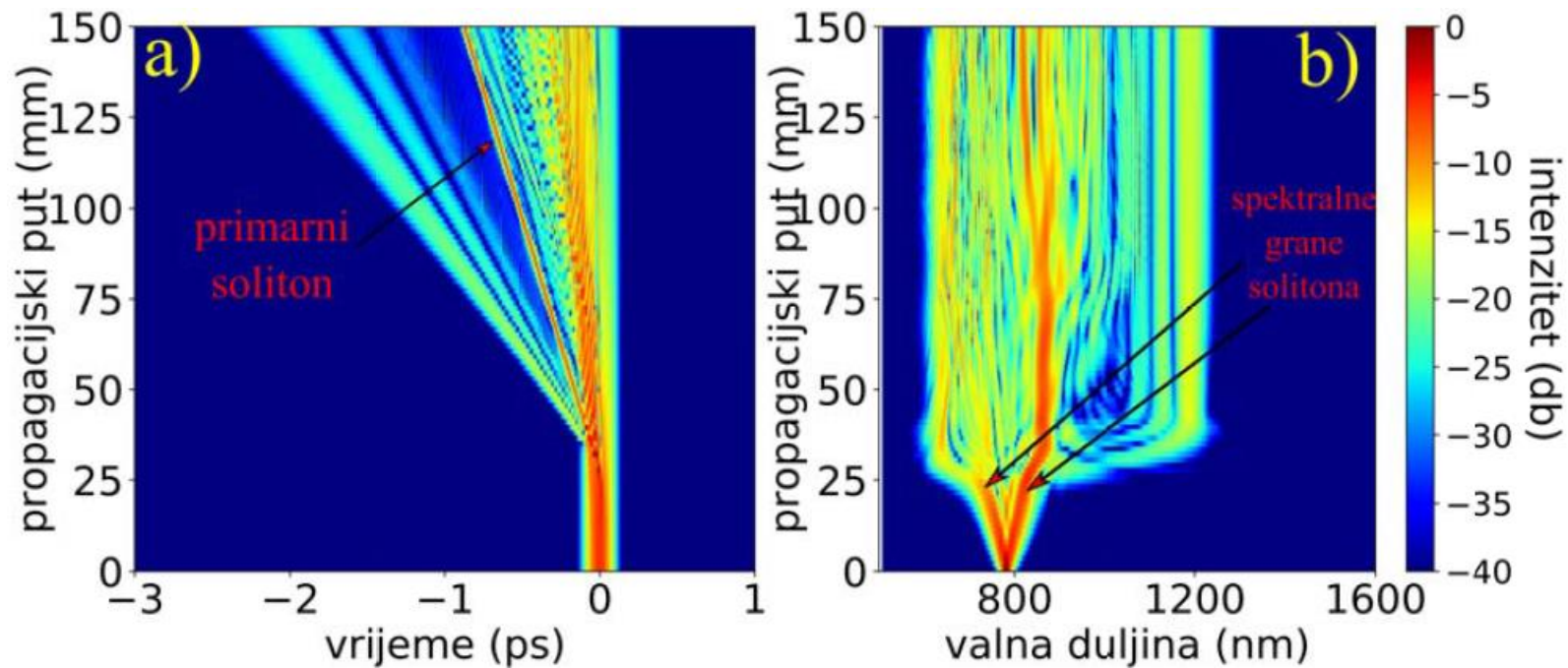
Rezultati simulacija:

$$\beta_2 = 0$$

$$\beta_3 = -0.05 \text{ps}^3 / \text{km}$$

$$\gamma = 50 \frac{1}{\text{W km}}$$

$z=28\text{mm}$
(početak fisije) \rightarrow



Samoustrmljenje (Self-steepening)

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial |u|^2}{\partial T} \right)$$

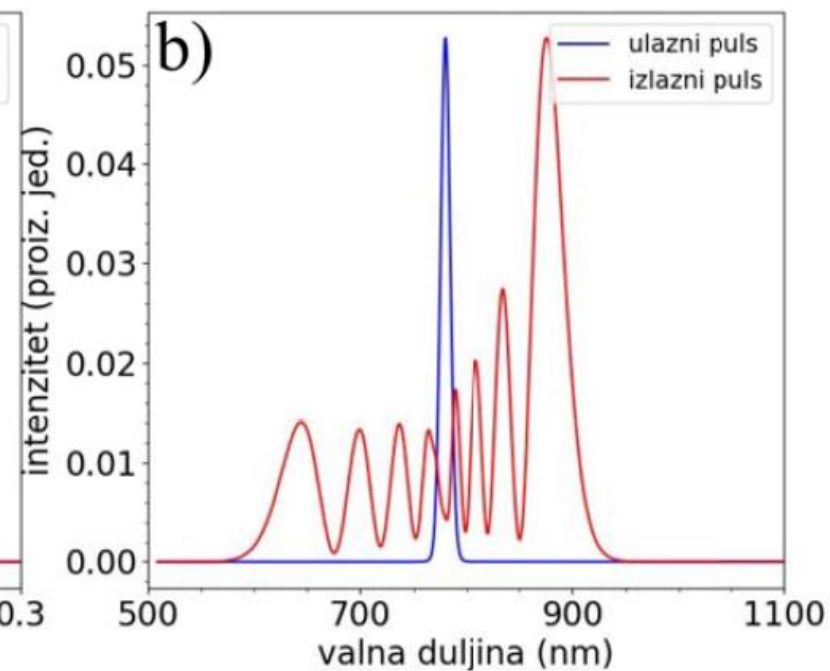
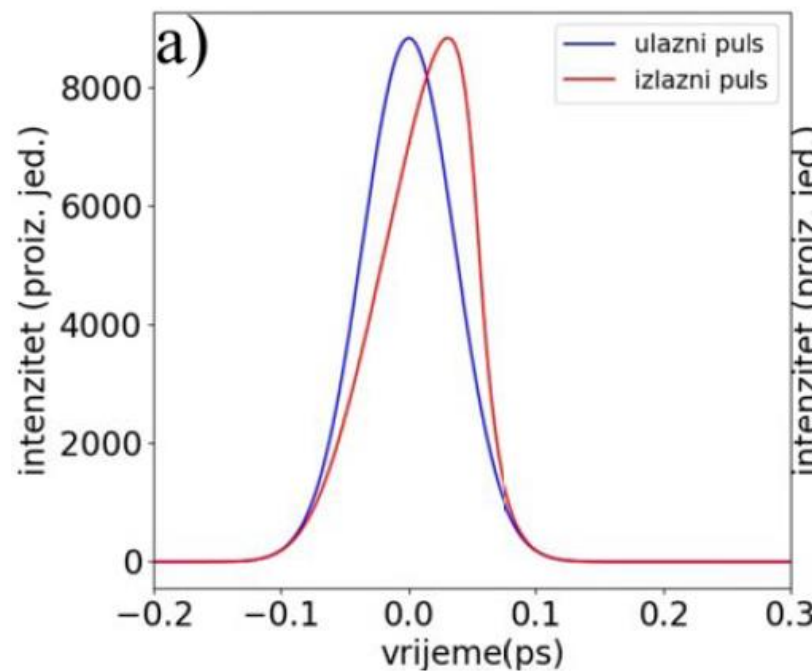
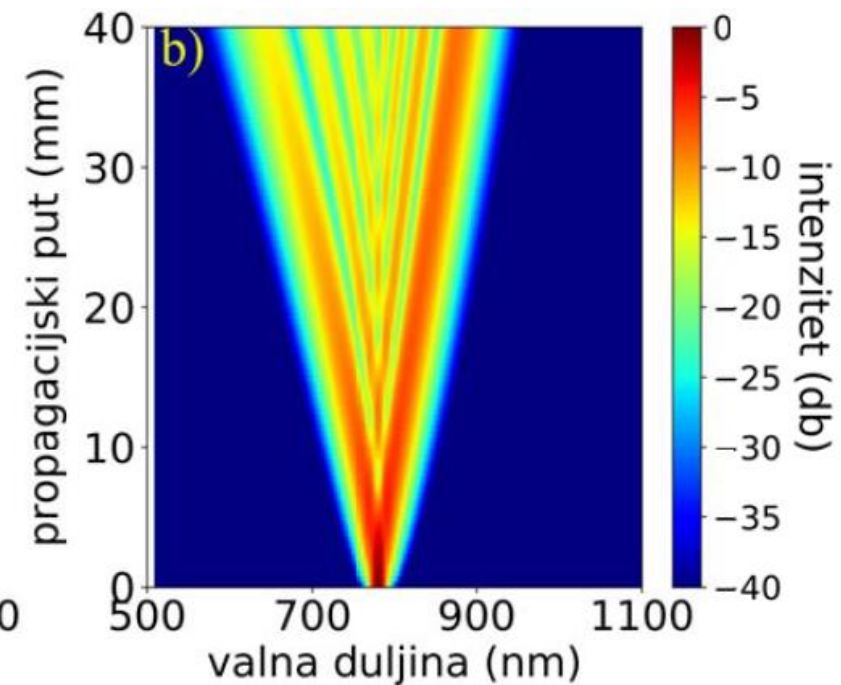
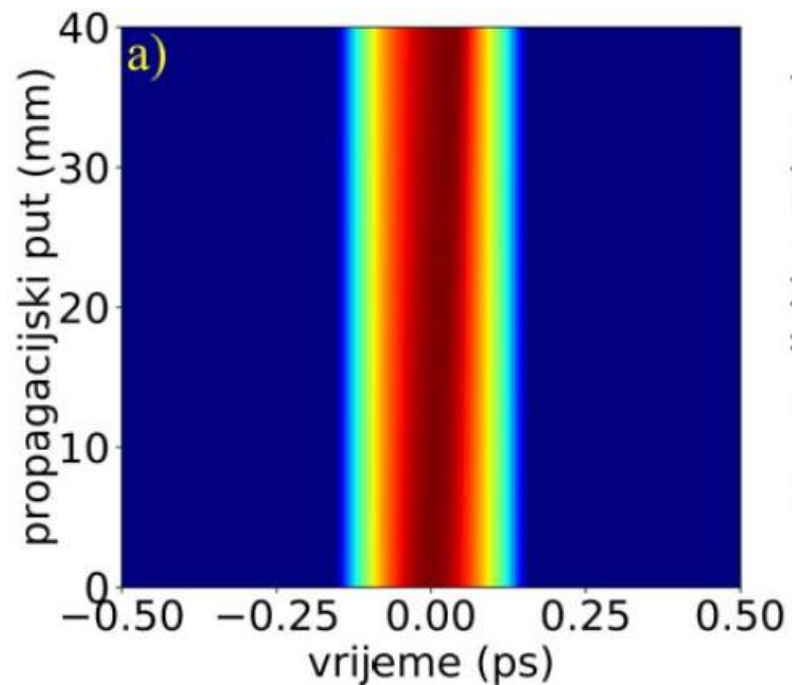
Nelinearni indeks loma \longrightarrow Grupna brzina ovisi o intenzitetu

Centar pulsa (najveći intenzitet) postaje najsporiji \longrightarrow Prateće krilo sustiže centar pulsa \longrightarrow Puls sve strmiji

Rezultati simulacija:

$$\begin{aligned}\beta_2 &= 0 \\ \beta_3 &= 0 \\ \gamma &= 70 \frac{1}{Wkm}\end{aligned}$$

$z=40\text{mm}$



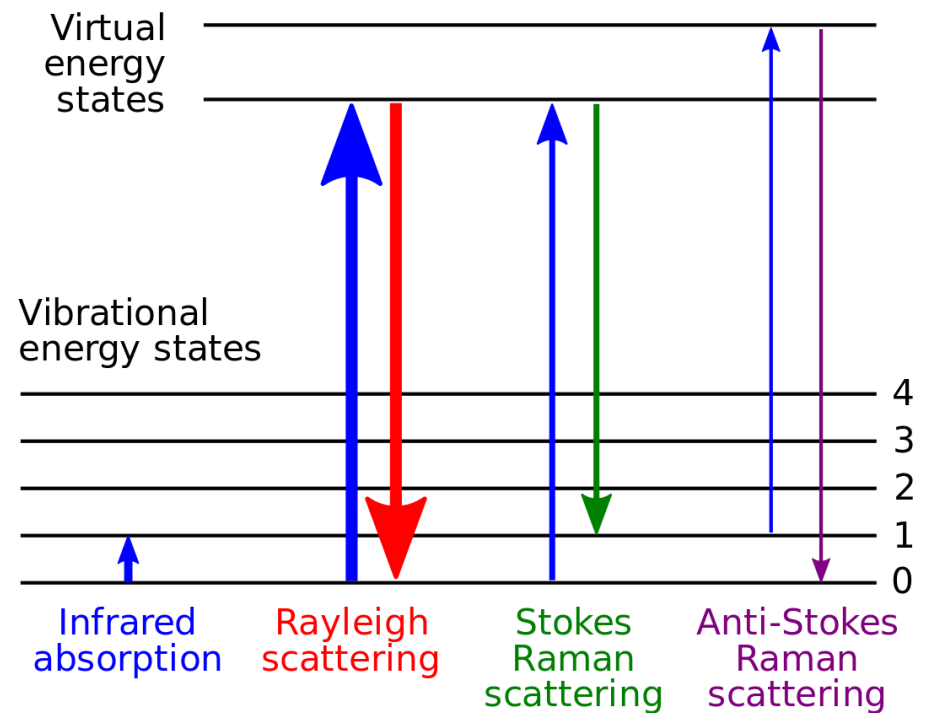
Raman raspršenje

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial T^2} - \frac{\beta_3}{3} \frac{\partial^3 u}{\partial T^3} = i\gamma \left(u|u|^2 + \frac{i}{\omega_0} \frac{\partial(|u|^2 u)}{\partial T} - T_R u \frac{\partial|u|^2}{\partial T} \right)$$

Neelastično raspršenje fotona na molekulama

Foton predaje energiju molekuli → Stokes Raman scattering

Molekula predaje energiju fotonu → Anti-Stokes Raman scattering



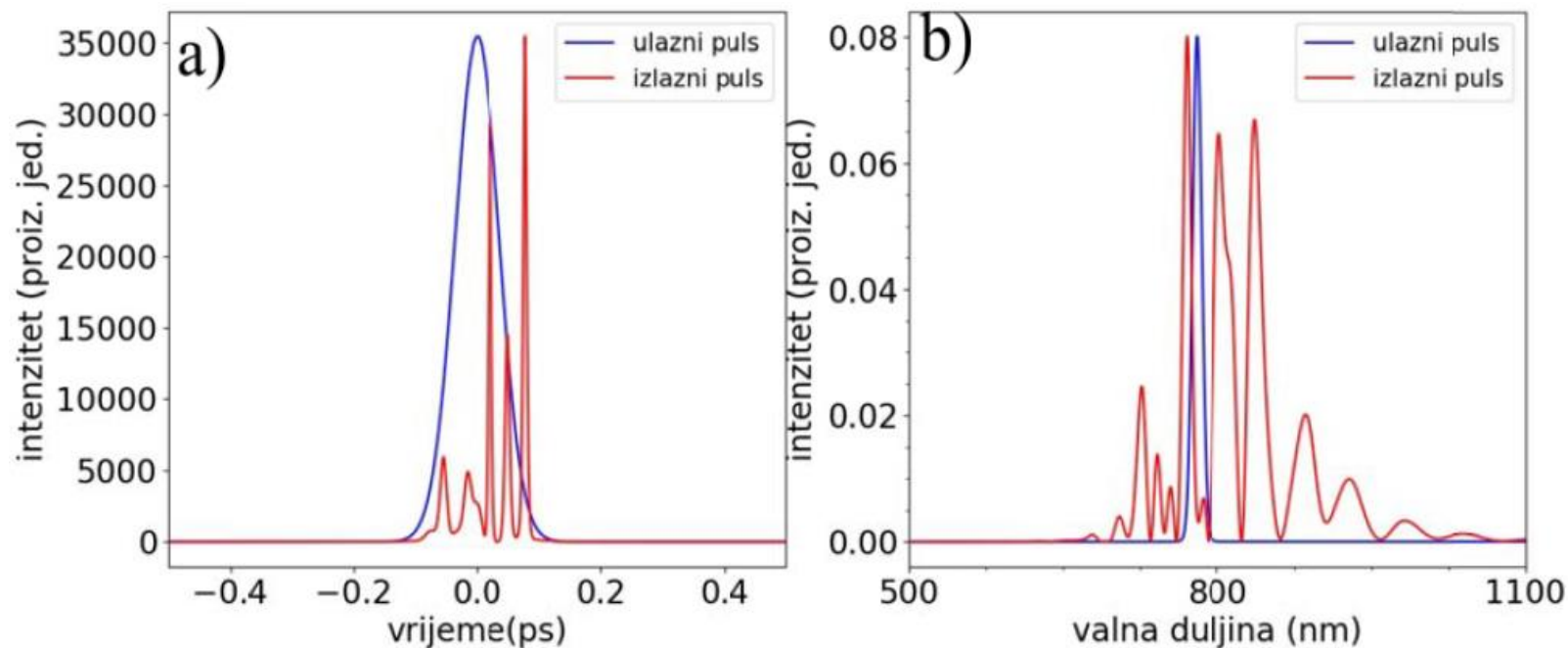
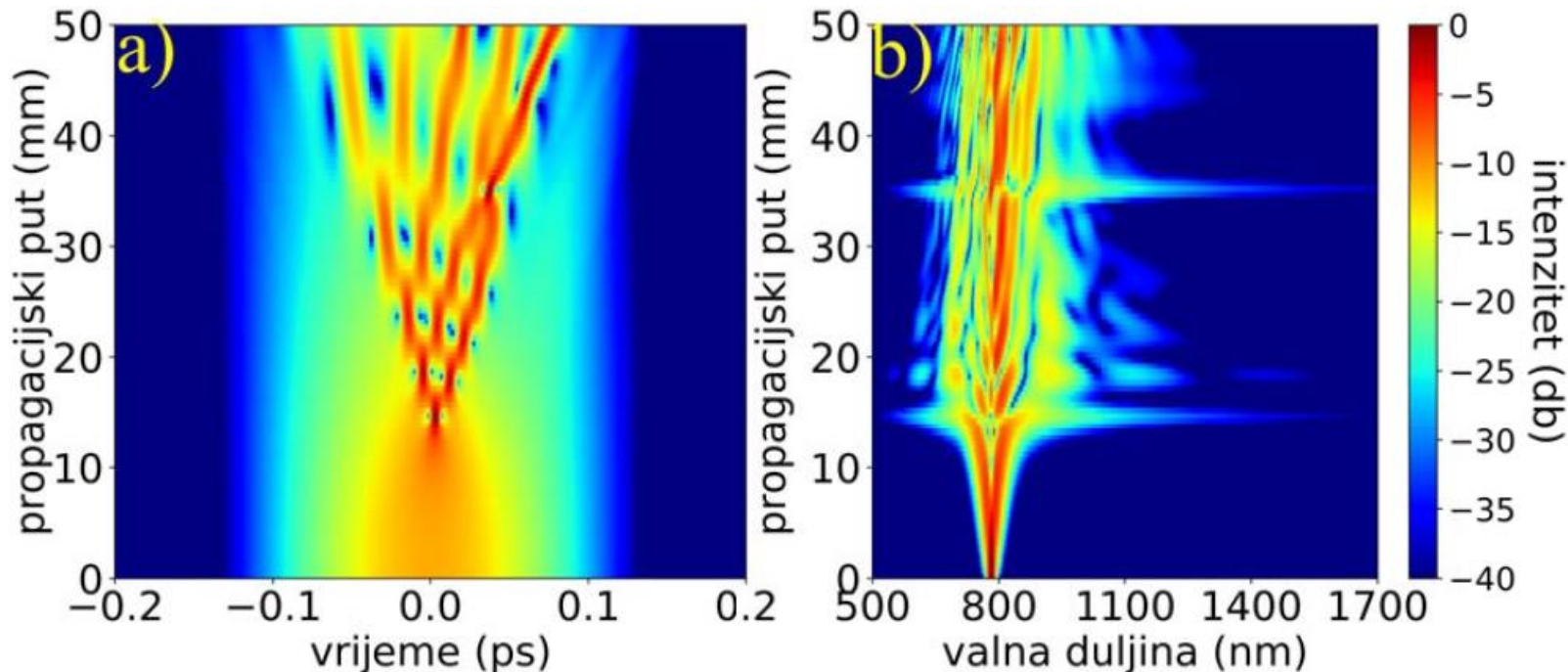
Rezultati simulacija:

$$\beta_2 = -15 \text{ps}^2/\text{km}$$

$$\beta_3 = 0$$

$$\gamma = 50 \frac{1}{\text{W km}}$$

$z=20\text{mm}$



Eksperimentalni postav

Izvor svjetlosti

Er:dopirani femtosekundni laser
valne duljine 1550 nm

Optičko vlakno

NL-PM-750

Duljina: 48cm

Promjer jezgre: $(1,8 \pm 0,3) \mu\text{m}$

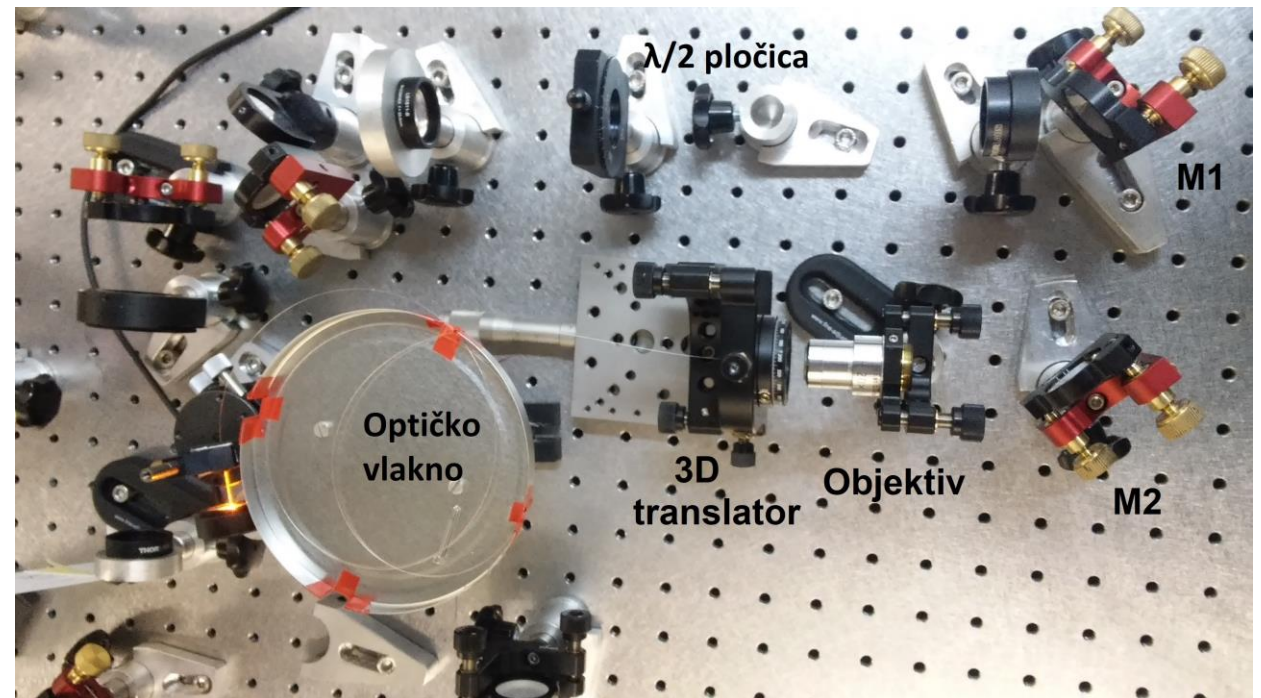
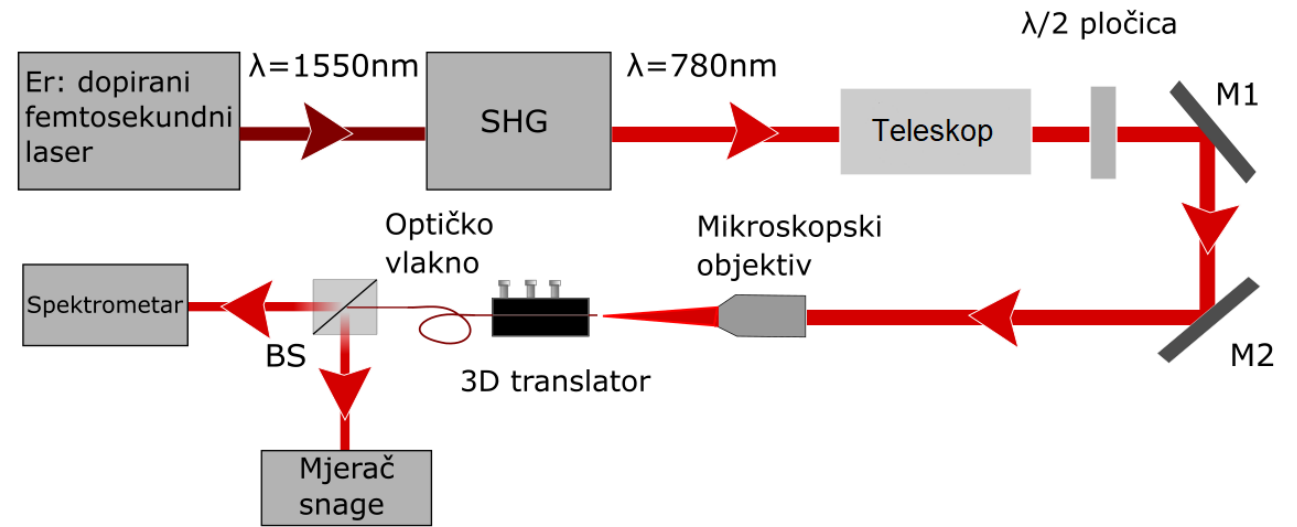
Promjer omotača: $(120 \pm 5) \mu\text{m}$

Num. apertura: (0.38 ± 0.05)

Objektiv:

Povećanje: 20x

Num. Apertura: 0.4

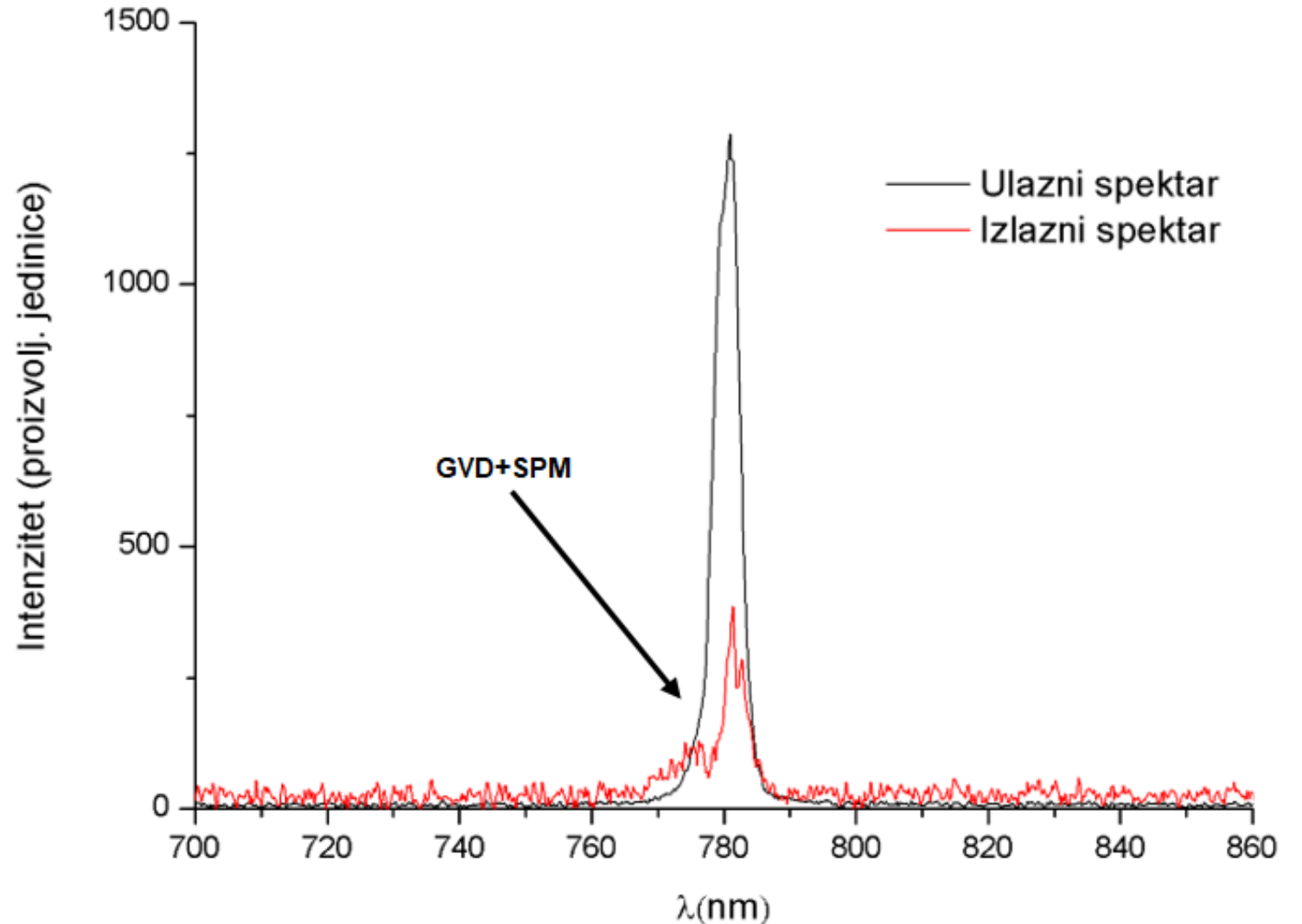


Rezultati (1)

Snaga: $640\mu W$

Vidljive blage oscilacije
i proširenje linije na 780nm
Zbog kombiniranog utjecaja
GVD i SPM članova

Ostali efekti nemaju utjecaja
jer je propušteni intenzitet
svjetlosti premali



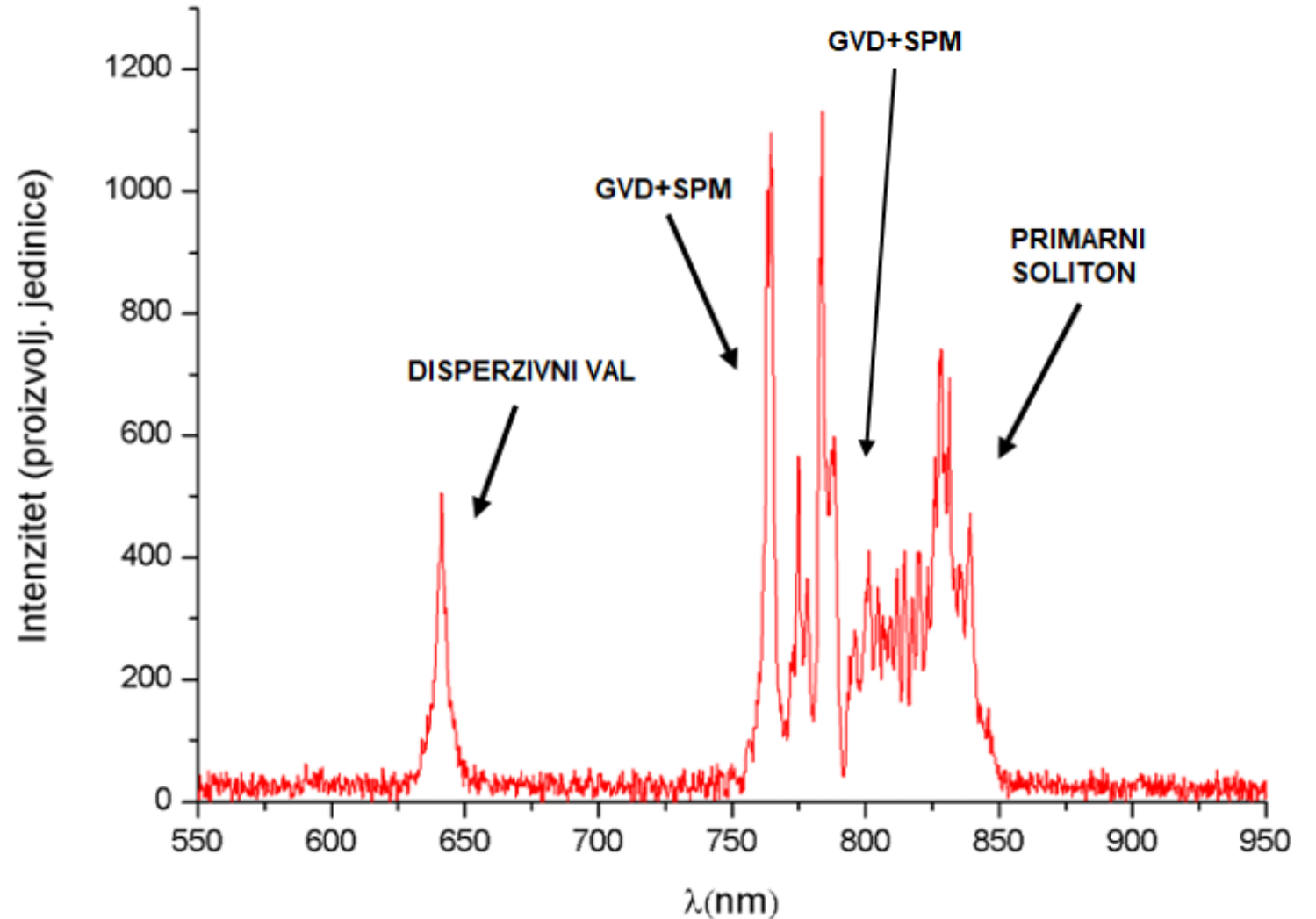
Rezultati (2)

Snaga: 4.3mW

Vidljiv utjecaj ostalih efekata
(osim GVD+SPM)

Prisutne jače oscilacije zbog
GVD+SPM

Vidljiv primarni soliton i njemu
pripadni disperzivni val



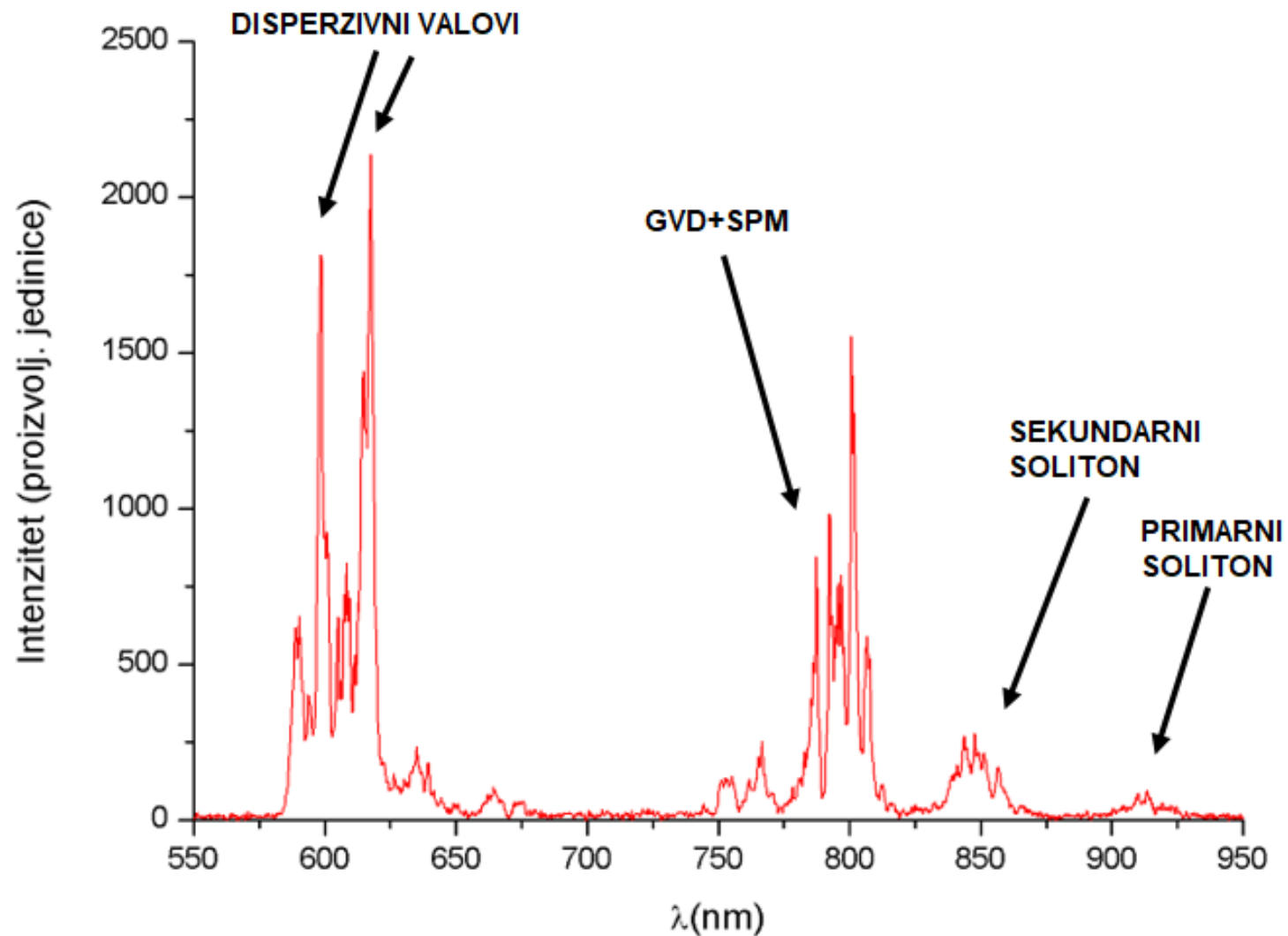
Rezultati (3)

Snaga: 10.21mW

Vidljiv utjecaj ostalih efekata
(osim GVD+SPM)

Prisutne jake oscilacije zbog
GVD+SPM

Vidljiv primarni i sekundarni soliton te
Njima pripadni disperzivni valovi

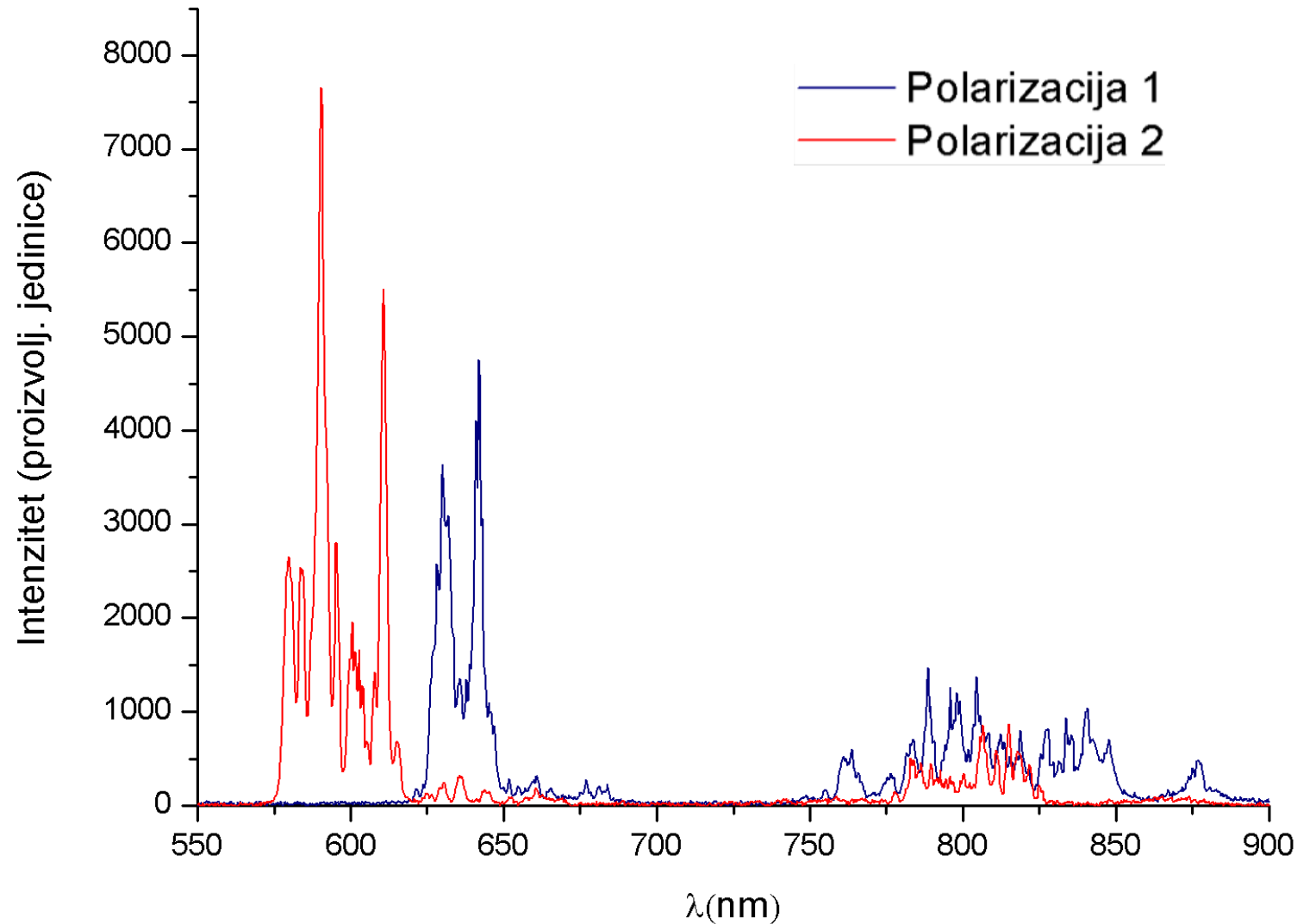


Rezultati (4)

Korištenjem $\lambda/2$ pločice moguće je mijenjati polarizaciju svjetlosti

Rezultat:

Superkontinuum ovisi i o polarizaciji ulazne svjetlosti



Zaključak

Teorijski proučeni pojedini članovi generalizirane nelinearne Schrödingerove jednadžbe

Izmjerena ovisnost superkontinuuma o snazi ulazne svjetlosti za 3 različite snage
Identificirani dijelovi superkontinuuma

Pokazana ovisnost o polarizaciji

Superkontinuum proširen do 580nm
(obuhvaća 632nm - HeNe)

Postoji mogućnost proširenja do 520nm
i stabilizacije frekventnog češlja putem
2f-3f samoreferentne metode

