Academia Romana

Componente plasmonice neliniare

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Abstract

Aceasta lucrare investigheaza un rezonator circular plasmonic care prezinta o neliniaritate de tip Kerr [2]. S-a demonstrat numeric si teoretic ca acest sistem prezinta instabilitati de tip Ikeda care conduc la aparitia unui regim de auto-oscilatie. Prin simulari numerice s-au pus in evidenta auto-oscilatile care prezinta durate de ordinul sutelor de femtosecunde.
S-a calculat teoretic regimul de bistabilitate al rezonatorului si s-au identificat regimurile de functionare ale acestuia ca functie de puterea undei incidente: regim stationar, regim de auto-oscilatie, regim haotic. De asemenea, s-a investigat acordabilitatea acestui sistem pentru a genera pulsuri cu frecvente diferite. Acest sistem poate prezenta aplicatii in generarea de radiatie de terahertz sa ca ceas optic cu pulsuri de ordinul sutelor de femtosecunde in circuite optice integrate.

Introducere - Plasmonica

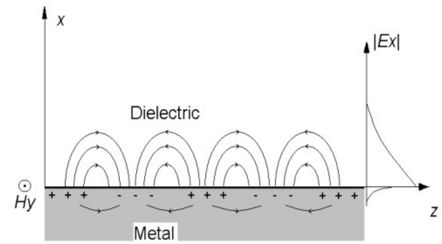
Plasmonica interactiunea radiatiei cu gazul de electroni liberi prezent in metale sau in oxizi de metale conductivi [1].

Excitatia rezultata din aceasta interactiune → plasmon – polariton de suprafata (SPP)

- Localizare puternica la interfata dielectric – conductor → confinarea radiatiei la dimensiuni mult mai mici decat lungimea de unda.

- Ghiduri de unda plasmonice

-Proprietati modale si de dispersie interesante: v_g<<c (slow modes), modul fundamental antisimetric, propagare left-handed: v_g sens opus v_f.



Aplicatii

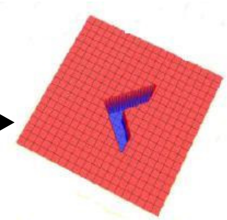
- prelucrarea semnalelor optice

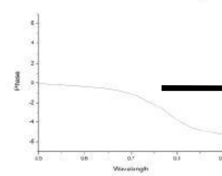
- larga integrare a circuitelor plasmonice (la o scala de ordinul nm)

- optica ultrarapida

- **Plasmonica neliniara**

- nanoantene, metamateriale, metasuprafete →





→ •Roxana Tomescu, Cristian Kusko, Mihai Kusko and Paul Schiopu, "FDTD simulations of plasmonic metasurfaces" , ImagineNANO Bilbao, Spain, March (2015).

1.Gramotnev, D. K. ; Bozhevolnyi, Sergey I. , Plasmonics beyond the diffraction limit, Nature Photonics 4 , 83, 2010

2. Cao and Mark Brongersma. Active Plasmonics: Ultrafast developments. Nature Photonics, January 2009.

3. Nature Photonics 6 , 11, 2012 Focus Plasmonics

Efecte neliniare – grad aditional de libertate pentru controlul excitatiei plasmonice

Controlul luminii cu ajutorul luminii – interactia foton foton facilitata de material

Martti Kauranen and Anatoly V. Zayats, Nature Photonics **6** 737 (2012)

Intensificarea campului la interfata metal - dielectric
Fenomene neliniare asociate gazului (lichidului Fermi) din metal
Timp de raspuns ultrarapid (fs)
Dispersia, caracterul modal, si rezonantele asociate structurilor plasmonice

Aplicatii

Conversie de frecventa
Generarea armonicii a doua (SHG)
Propagare de solitoni
Comutatie optica
Modularea semnalelor optice
Metamateriale neliniare
Sisteme care prezinta autopulsatie – generare de pulsuri

→ Circuite integrate plasmonice cu grad ridicat de integrare cu timp de raspuns ultrascurt

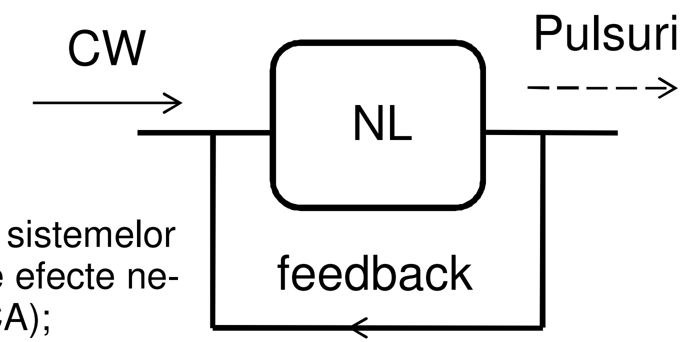
\+

Functionalitati noi

Autopulsatie

Input CW → Output pulsuri periodice sau haotice

Element neliniar + bucla de feedback



Curba de histeresis
Metoda bifurcatiilor Hopf
Teoria modurilor cuplate
Ecuatia Schrodinger neliniara discreta

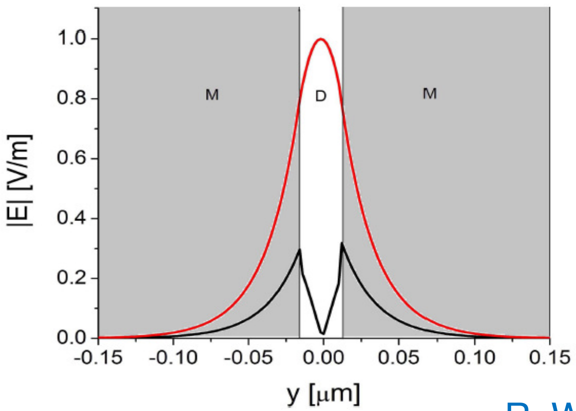
Metoda FDTD
- dificultate in interpretarea sistemelor AP care prezinta o serie de efecte ne-liniare (Kerr, TPA, FCD, FCA);
- rezultate exacte (in limita aproximatiilor numerice)

J. Y. Gao , L. M Narducci, L. S. Schulman, M. Squicciarini, and J. M. Yuan, "Route to chaos in a hybrid bistable system with delay", Phys. Rev A 28, 2910 (1983)

Sisteme AP in fotonica: Rezonatoare Fabry – Perot; Cristale fotonice; Cavitati cuplate

S. Chen, L. Zhang, Y. Fei and T. Cao, "Bistability and self-pulsation phenomena in silicon microring resonators based on nonlinear optical effects", Opt. Express 20, 7454,(2012
B. Maes, M. Fiers, and P. Bienstman, "Self-pulsing and chaos in short chains of coupled nonlinear microcavities", Phys. Rev. A 80, 033805 (2009)

Element neliniar – ghid de unda plasmonic



Ghiduri plasmonice liniare de tip metal – dielectric – metal

Grad de confinare ridicat
Caracteristici modale interesante
Cut off la frecvente ridicate
Slow modes
Propagare negativa

$v_g = 0.04c$

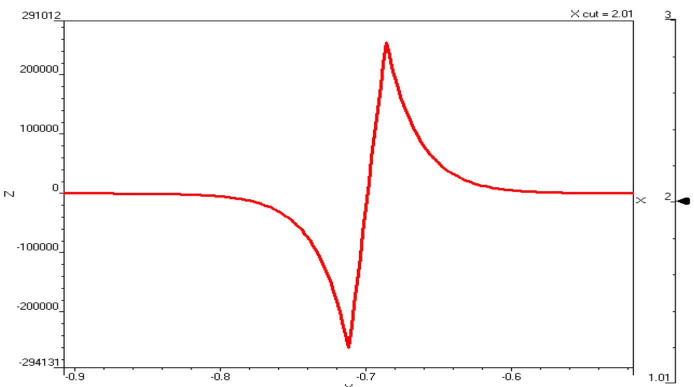
Intensificarea efectelor neliniare

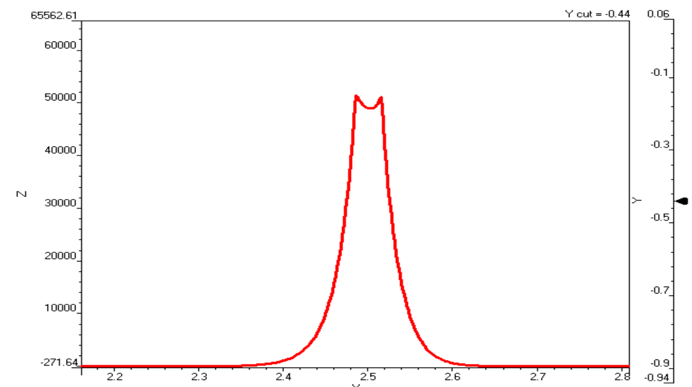
R. W. Boyd, "Material slow light and structural slow light: Similarities and differences for nonlinear optics," *J. Opt. Soc. Amer. B, 28,* 38, (2011).

$\rho=\varepsilon_m/\varepsilon_d$

$\rho<1$ Mod fundamental antisimetric

$\rho>1$ Mod fundamental simetric





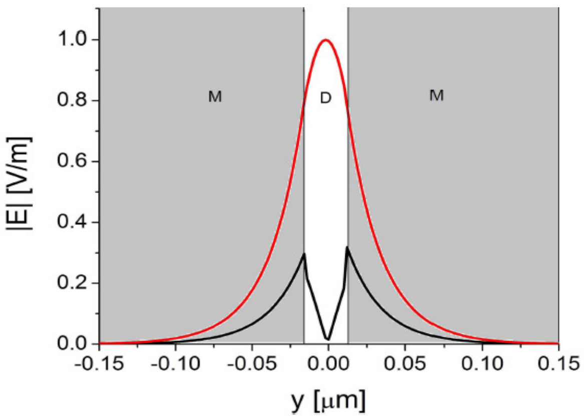
Ghid de unda plasmonic neliniar

Ghiduri plasmonice neliniare de tip metal – dielectric – metal

Dielectric – neliniaritate de tip Kerr

- aparitia unor caracteristici modale diferite de cazul liniar
- competitie intre modurile neliniare
- rupere de simetrie si puncte de bifurcatie
- moduri cu viteza de grup mica (slow modes)

A. R. Davoyan, I. V. Shadrivov, and Y. S. Kivshar, “Nonlinear plasmonic slot waveguides”, Opt. Express 16, 21209 (2008)

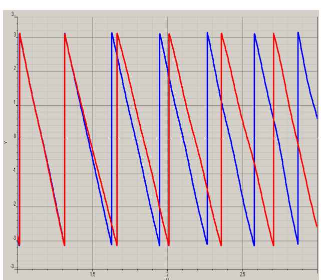


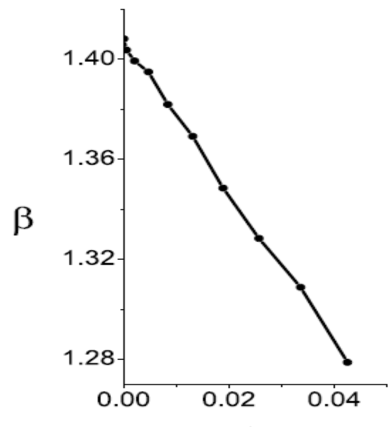
Mod fundamental antisimetric

$$\Delta n = 3/4n\chi^{(3)}|E_z|^2.$$

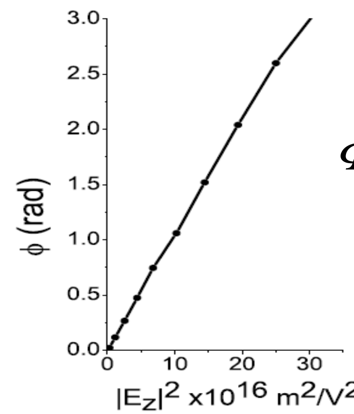
$$\chi(3) = 10^{-18}\, m^2/V^2$$

$$\varepsilon_{NL} = 12.25. \quad A_{III}B_V.$$





Dependenta constantei de propagare β a ghidului de unda neliniar fata de intensitatea campului electromagnetic.



Avansul de faza a unei excitatii SPP care se propaga intr-un ghid MDM neliniar ca functie de intensitatea campului

$$\Phi = \alpha|E_z|^2.$$

$$\alpha = 0.11\cdot 10^{-16}\, rad\cdot m^2/V^2$$

Rezonator circular plasmonic neliniar

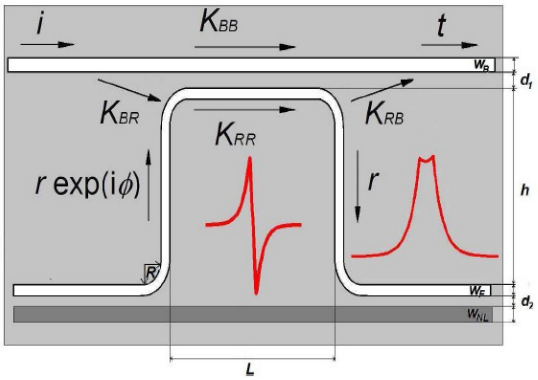
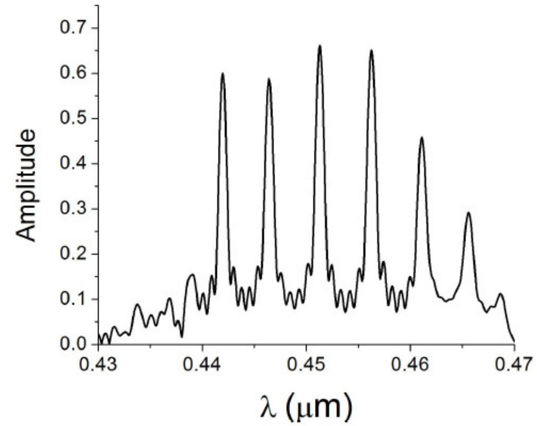
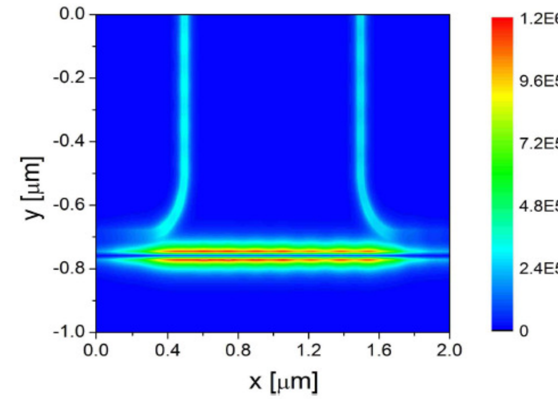


Diagrama rezonatorului plasmonic

Contracuplaj ghid feedback – ghid NL



Caracteristica spectrala Q=1000



Simulare FDTD a Hy

Parametri geometrici

w_{NL} = 26 nm
w_F=30 nm
d_1=80 nm
d_2=66 nm
L=600 nm
H=700 nm

Parametri de material

Metal Au
Permitivitate Drude
$\varepsilon(\omega) = \infty - \omega_p^2/(\omega^2 - i\gamma\omega)$
$\omega_p = 1.346 \cdot 10^{16}$ rad/s
$\gamma = 4.0 \cdot 10^{12}$ rad/s

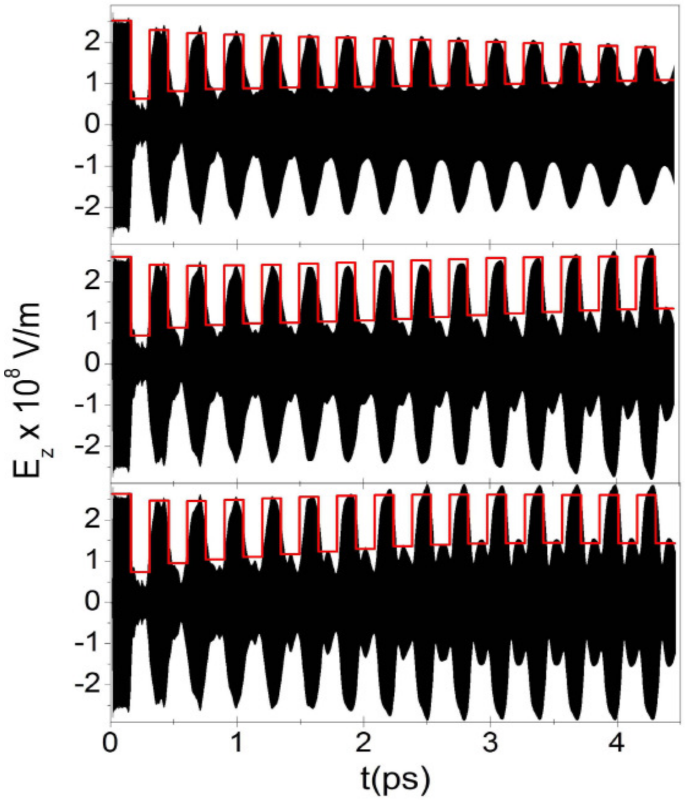
Parametri functionali

K_{BR}=0.27
K_{RR}=0.94
Φ=2.34 rad
$\alpha = 0.11 \cdot 10^{-16}$ rad·m²/V²
a=0.9
λ=444.6 nm

Y. Gong and J. Vuckovic, "Design of plasmon cavities for solid-state cavity quantum electrodynamics applications", Appl. Phys. Lett. 90, 033113 (2007)

Temperaturi joase – reducerea ratei de imprastiere γ

Raspunsul temporal al rezonator circular plasmonic neliniar; Simulari FDTD Calcule analitice



Raspunsul temporal ; linia neagra simulari FDTD; linia rosie – calcule analitice

Cazul liniar ⟶ Stare stationara

$$r^{(n)} = K_{BR}i + aK_{RR}r^{(n-1)}\exp(i\phi)$$

Cazul neliniar ⟶ Autopulsatii

$$r^{(n)} = K_{BR}i + aK_{RR}r^{(n-1)}\exp(i\phi)\exp(i\alpha|r^{(n-1)}|^2).$$

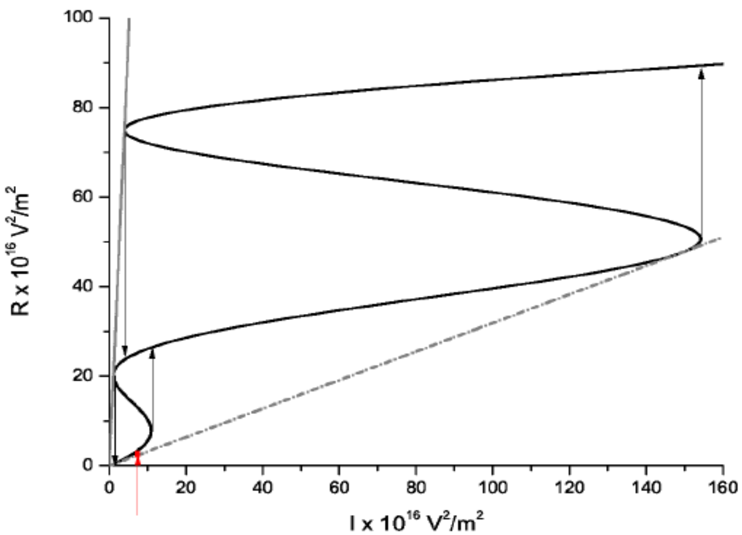
Relatie iterativa neliniara

Instabilitate Ikeda

K. Ikeda, “Multiple-valued stationary state and its instability of the transmitted light by a ring cavity system,” *Opt. Commun.*, ***30***, 257, (1979).
K. Ikeda and O. Akimoto, “Instability leading to periodic and chaotic self-pulsations in a bistable optical cavity,” *Phys. Rev. Lett.*, ***48***, 617, (1982)

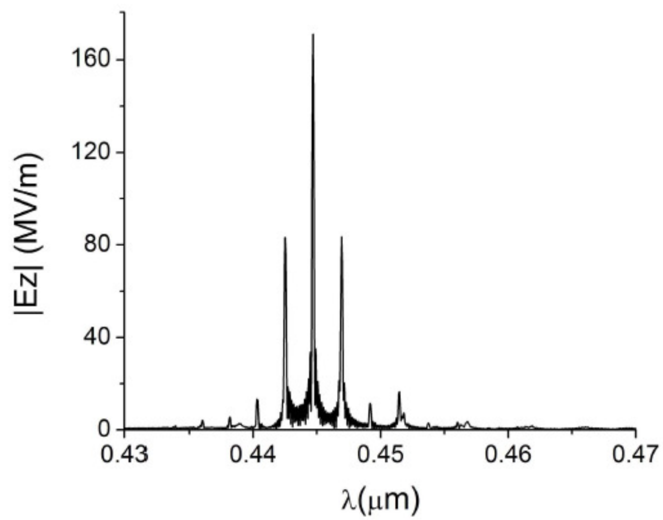
Pulsuri de ordinul sutelor de femtosecunde

Diagrama de bistabilitate; Raspunsul in frecventa



Intensitatea campului in interiorul rezonatorului ca functie de campul de input

- Forma de tip S; panta negativa; zona de bistabilitate
- Linia rosie reprezinta punctul de operare al rezonatorului.
- Ramura stabila a diagramei – caracteristica standard a oscilatiilor Ikeda



Raspunsul in frecventa (lungime de unda) a rezonatorului plasmonic neliniar – Comb diagram

$\Delta\lambda$ = 2.2 nm, Δf = 3.3 THz

$$|r|^2 = \frac{K_{BR}^2 |i|^2}{1 - 2aK_{RR}\cos(\phi + \alpha|r|^2) + a^2 K_{RR}^2}$$

Acordabiltatea duratei pulsurilor

Dispersia puternica a ghidului plasmonic MDM

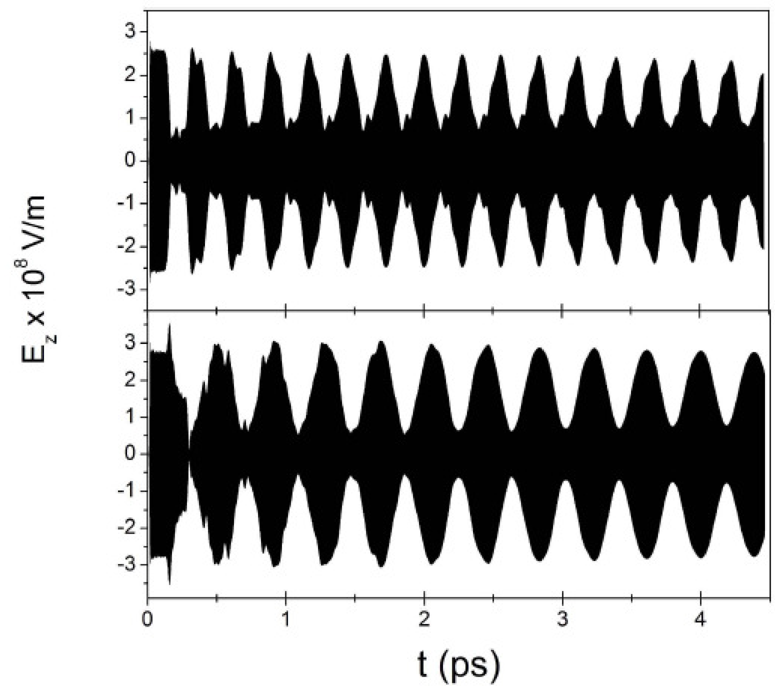
Variatia puternica a vitezei de grup cu lungimea de unda

Posibilitatea acordarii duratei pulsurilor cu λ campului de input

275 fs pentru *λ = 454.2 nm*

380 fs pentru *λ = 441 nm.*

300 fs pentru *λ = 444,6 nm.*



Raspunsul temporal al rezonatorului circular plasmonic neliniar pentru doua lungimi de unda a campului de input.

Analiza diagramei de bistabilitate si a diferitelor regimuri de functionare

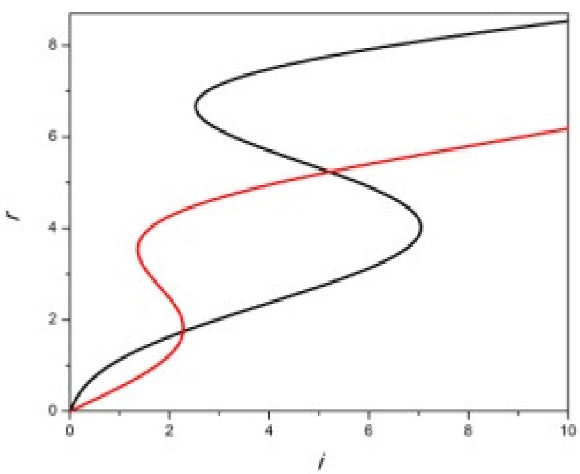
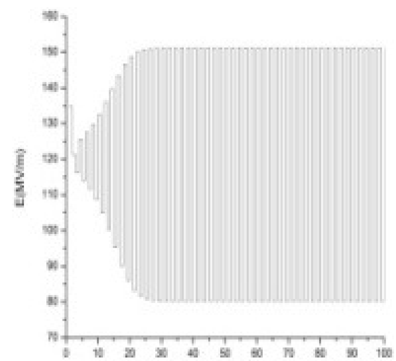
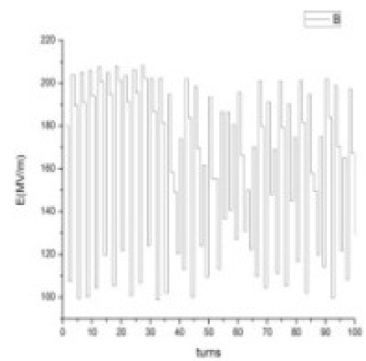


Diagrama de bistabilitate
α=0.9 rad.m^2/MV^2,
KRR=0.4
ϕ=0.2 (linia neagra)
$\phi=\pi-0.2$ (linia rosie)

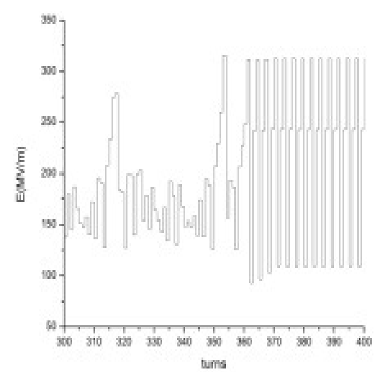


E=150 MV/m

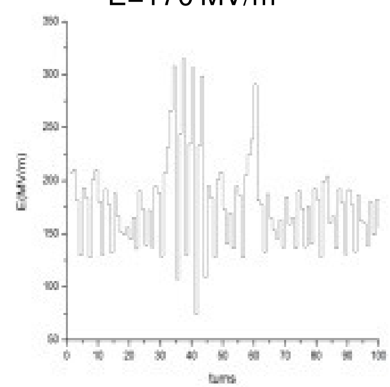


E=170 MV/m

Caz 1 ϕ=0.2 rad



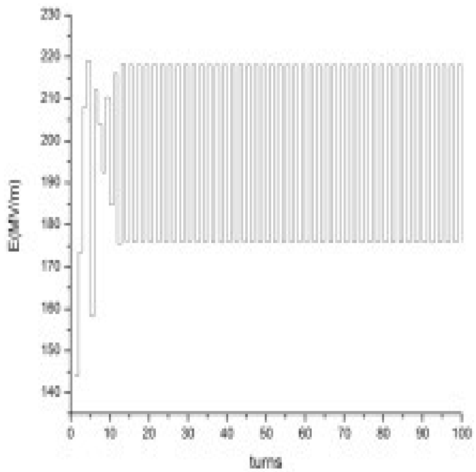
E=230 MV/m



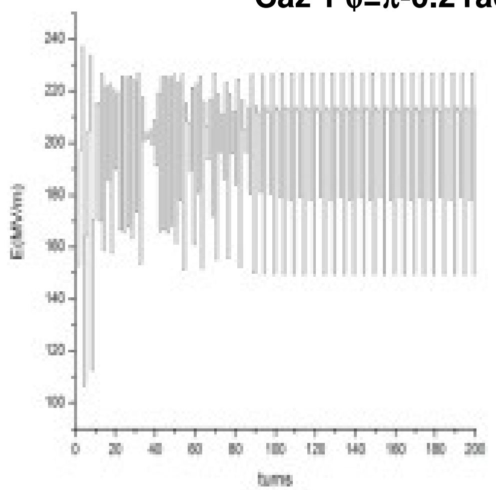
E=231 MV/m

Calcule analitice utilizand relatia Ikeda

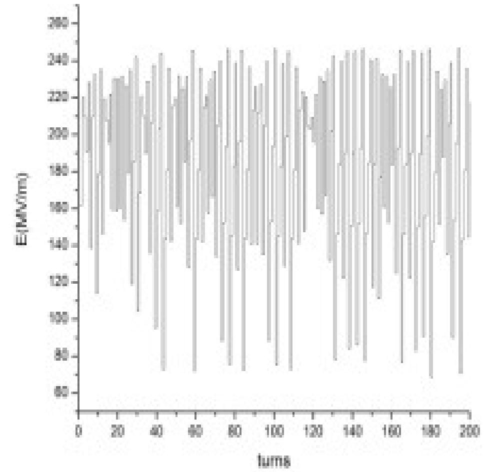
Caz 1 $\phi=\pi-0.2$ rad



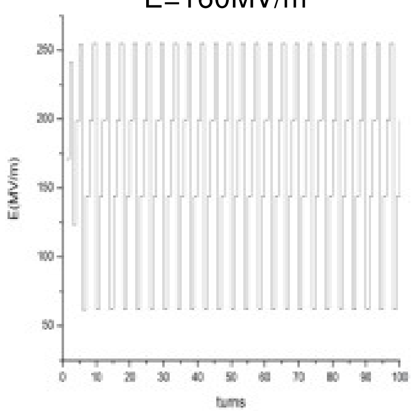
E=160MV/m



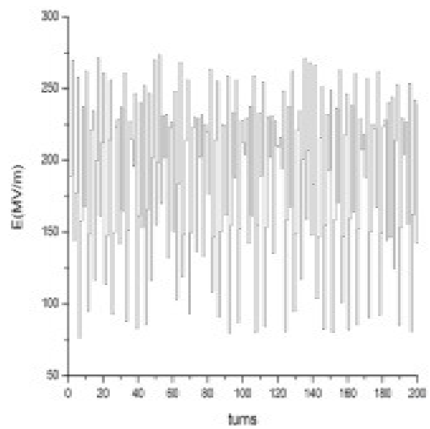
E=170MV/m



E=180MV/m



E=190MV/m



E=210 MV/m

Regim de autopulsatie cu doua nivele

Regim haotic

Regim de autopulsatie cu mai multe nivele

Concluzii

- Regim auto – pulsatoriu pentru rezonator circular plasmonic neliniar
- Intensificarea efectelor neliniare Kerr intr-un ghid plasmonic de tip MDM
- Variatia indicelui nonlinear $\Delta n=0.01$ compatibila cu cea din semiconductori de tip AIIIBV
- Generare de pulsuri cu perioada acordabila de ordinul a sute de femtosecunde
- Instabilitate de tip Ikeda
- Ruta catre obtinerea de haos determinist
- Posibile aplicatii: generare de THz, ceasuri optice pentru circuite integrate plasmonice sau fotonice

•Cristian Kusko “Self-Pulsation in a Nonlinear Plasmonic Ring Resonator”,
IEEE Journal of Quantum Electronics, **49**, 1080 (2013).

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