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Metamaterials for the Enhancement of Light-Matter Interactions

Ilya Vitebskiy (AFRL/RYD)

AFOSR PO: Dr. Arje Nachman

Topics Covered:

1. Unidirectional Light Amplification and Lasing in Active Nonreciprocal Structures

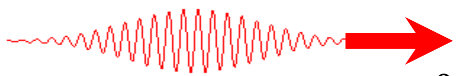
2. Omnidirectional Free-Space Isolators

3. **Enhanced Photonic Limiters and Switches Based on Nonlinear and Phase-Changing Materials**

Unidirectional Light Amplification and Lasing in Active Nonreciprocal Structures

There are two different definitions of electromagnetic unidirectionality:

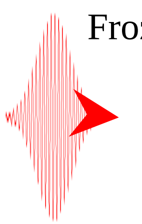
1. All propagating waves have only positive (or only negative) group velocity



$v_g > 0$

F. Haldane & S. Raghu (2006)

2. The group velocity is zero for one of the two directions of propagation

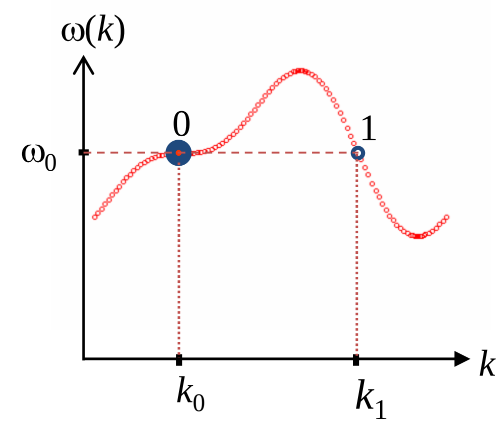


Frozen mode

$v_g = 0$

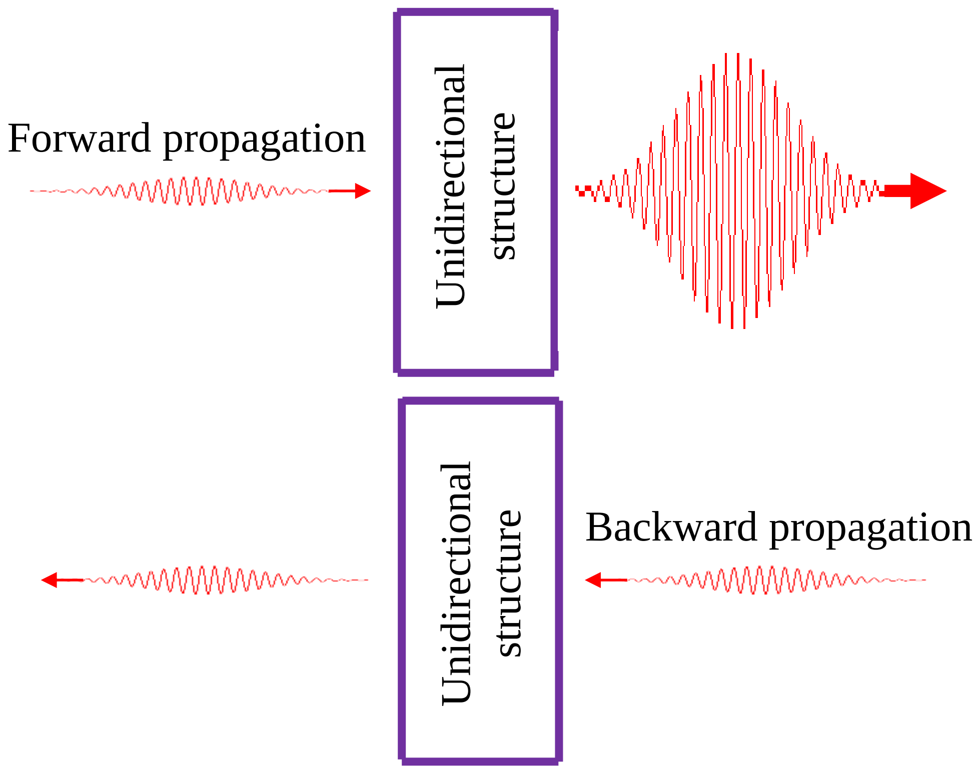
Fast mode

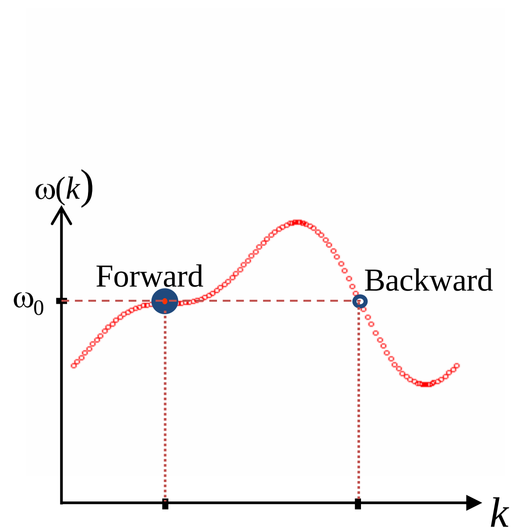
$v_g < 0$



Figotin & Vitebskiy (2001, 2003)

Light amplification and lasing in unidirectional media with active components





1. Below lasing threshold, only forward-propagating light is amplified (unidirectional amplification)
2. Above lasing threshold – immunity to back scattering (no need in optical isolation)
3. Independence of the output frequency on the structure size and the boundary conditions

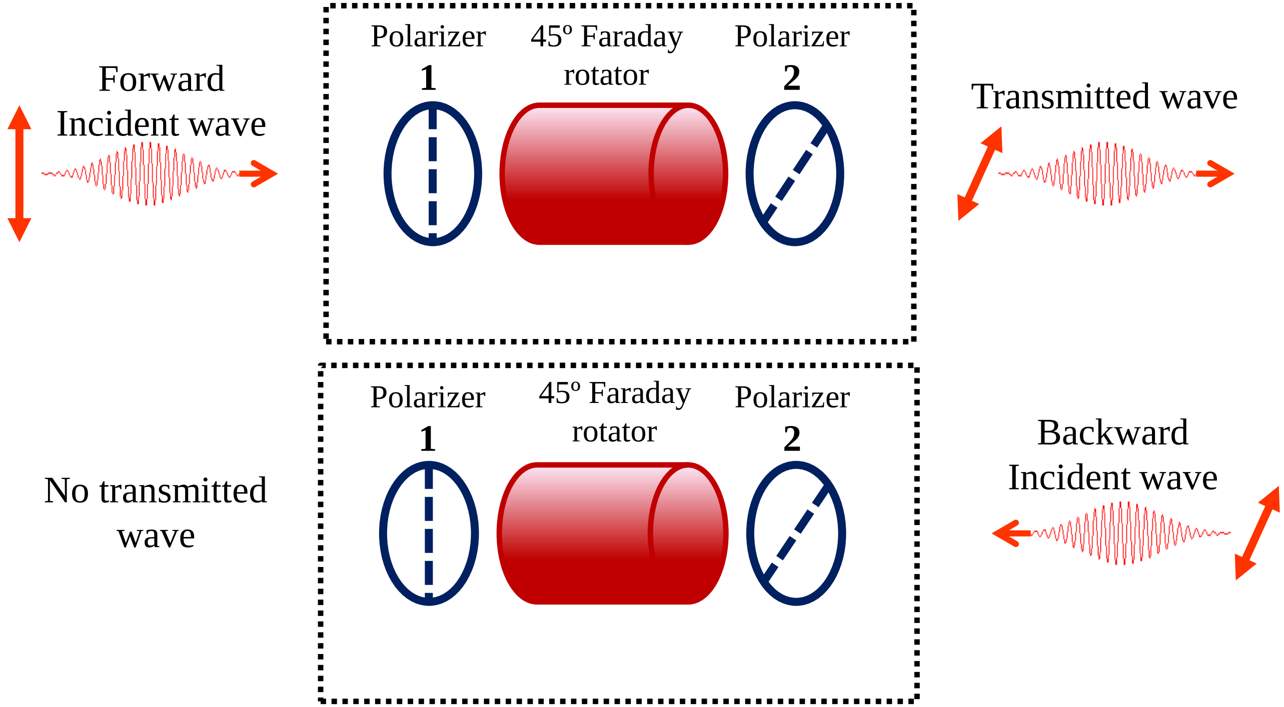
Publications:

1. H. Ramezani, S. Kalish, I. Vitebskiy, T. Kottos. *Unidirectional Lasing Emerging from Frozen Light*. Phys. Rev. Lett. 112 (2014) .

2. H. Li, I. Vitebskiy, T. Kottos. *Frozen mode regime in finite periodic structures*. Phys. Rev. B96, 180301(**R**) (2017)

A Free-Space Omnidirectional Isolator

Free-Space Isolators



Forward propagating wave passes through

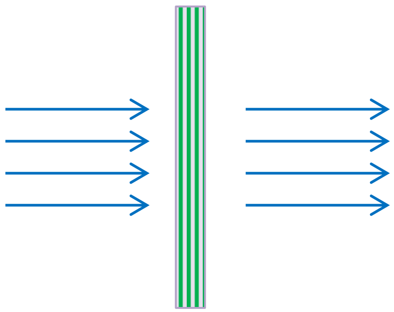
Backward wave gets stopped by polarizer 1

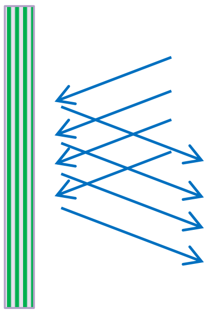
<u>We address the following basic problem</u>:

Common free-space isolators only perform for light propagating along the optical axis. At oblique (off-axis) incidence they fail.

A Concept of Wide-Aperture Omnidirectional Isolator

Forward propagating waves pass through

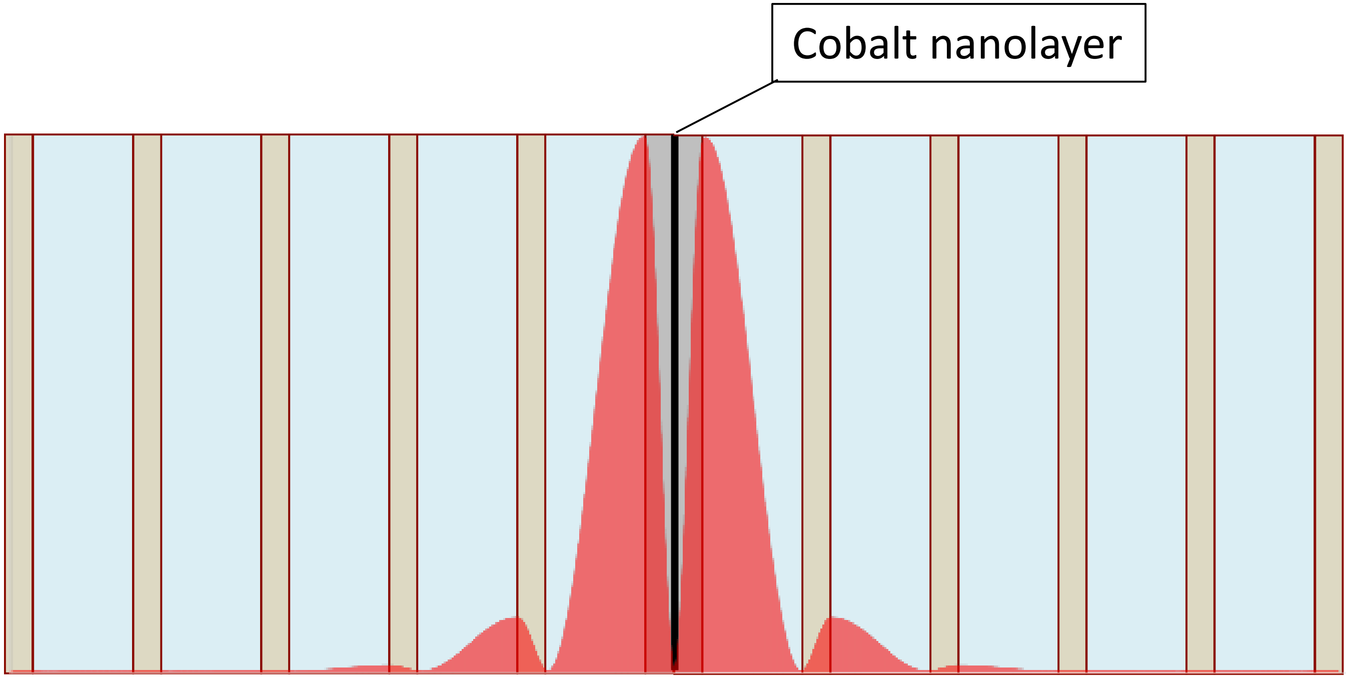




Backward propagating waves are reflected back to space regardless of the direction of incidence.

One proposed design uses a ferromagnetic metallic nanolayer (such as cobalt) incorporated in an asymmetric resonant cavity with high Q-factor. The metallic nanolayer location coincides with nodal point of the resonant field distribution. The design provides a broad-band and omnidirectional rejection of the backward-propagating radiation.

Intuitive Explanation of the Effect of Resonant Transmission of a symmetric High-Q Cavity with a Metallic Nanolayer

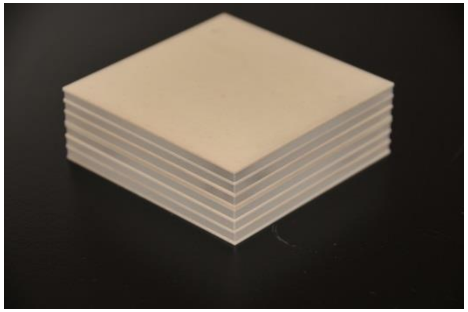


Field profile of the localized (defect) mode. The defect in the middle is composed of a pair of dielectric layers (dark grey) separated by a metallic nanolayer (the black line). The metallic nanolayer is located at the nodal point of the localized mode and, for this reason, the localized mode interaction with the metallic nanolayer is negligible. This explains a perfect resonant transmittance of the layered structure at the localized mode frequency. By contrast, the same metallic nanolayer taken out of the layered structure (a stand-alone nanolayer) is totally opaque at the same frequency range (**see the next slide**).

Resonant Transmission via Localized (Defect) Mode in a Photonic Layered Structure with and without Metallic Nanolayer

(*A. Chabanov and students*)

$(HL)^3HMH(LH)^3$

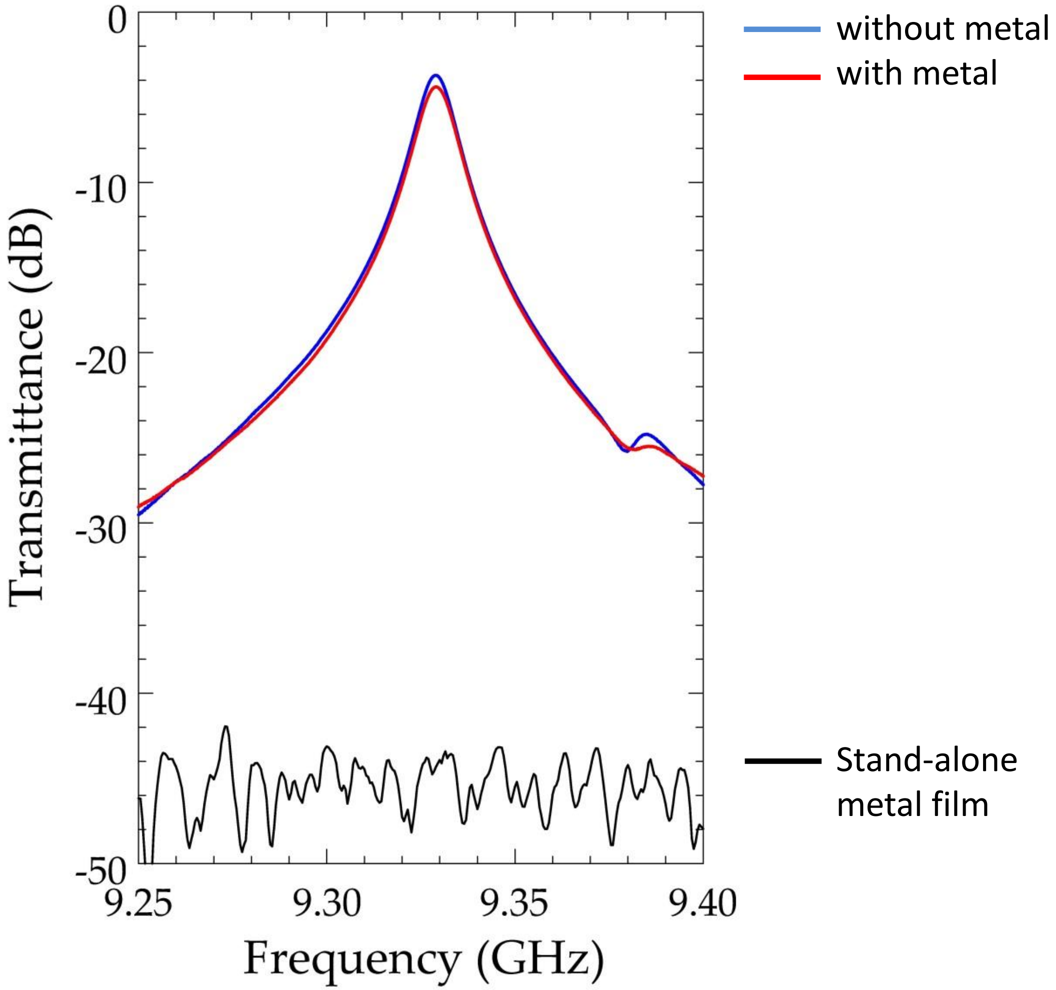


<u>MW ceramics:</u>
1 mm; $\varepsilon_1 = 38$; loss tangent, 2×10^{-4}

<u>Glass:</u>
4 mm; $\varepsilon_2 = 3.8$; loss tangent, 7×10^{-6}

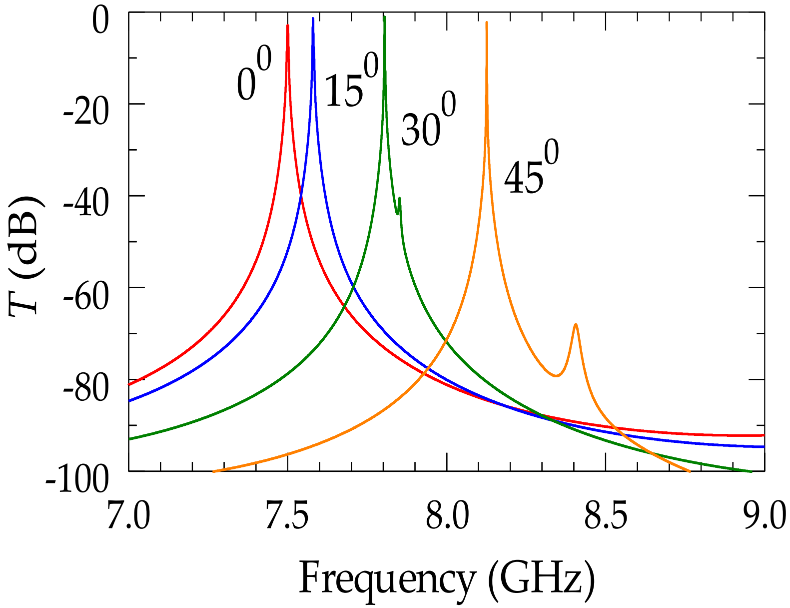
<u>Co90Fe10:</u>
150 nm; $\sigma = 1 \times 10^{16}\ s^{-1}$

<u>Cavity quality factor</u>, Q = 800



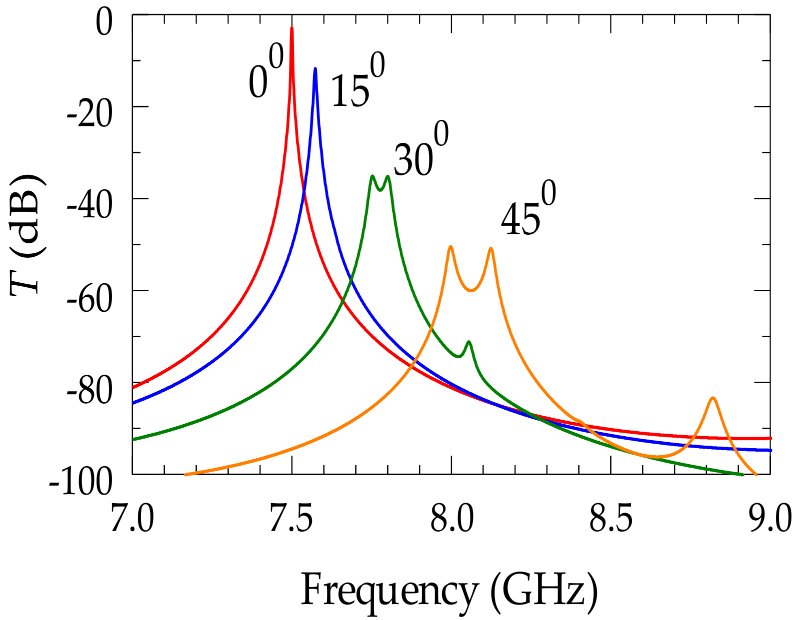
Extreme Directionality of the Metal-Dielectric Multilayers: Symmetric Structure vs. Asymmetric Structure

Symmetric structure
with metallic nanolayer



Blue shift of resonant
transmission at oblique incidence

Asymmetric structure
with metallic nanolayer

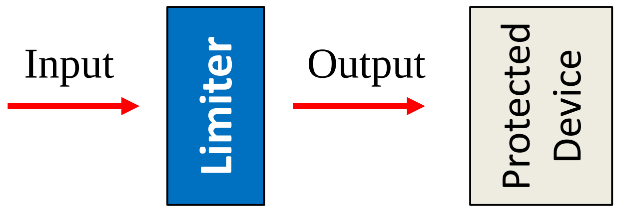


Strong suppression of resonant
transmission at oblique incidence

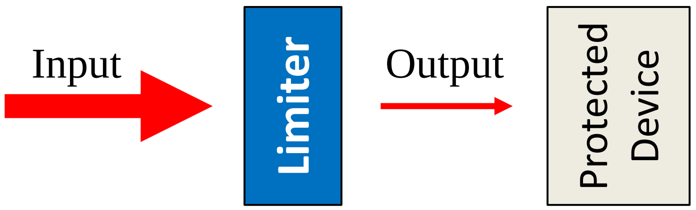
Enhanced Photonic Limiters and Switches.

Light Propagation in Photonic Structures with Phase-Changing Components.

Definition of a Limiter / Power Switch

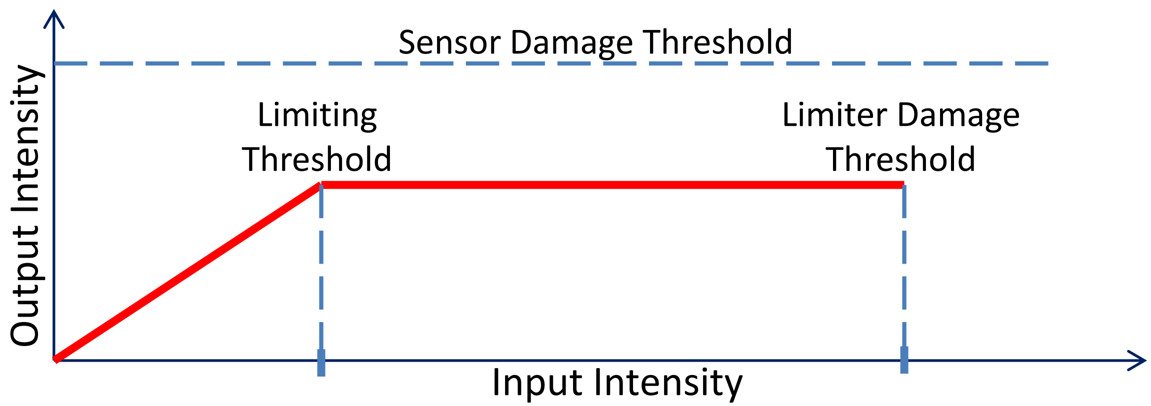


Low intensity light is transmitted

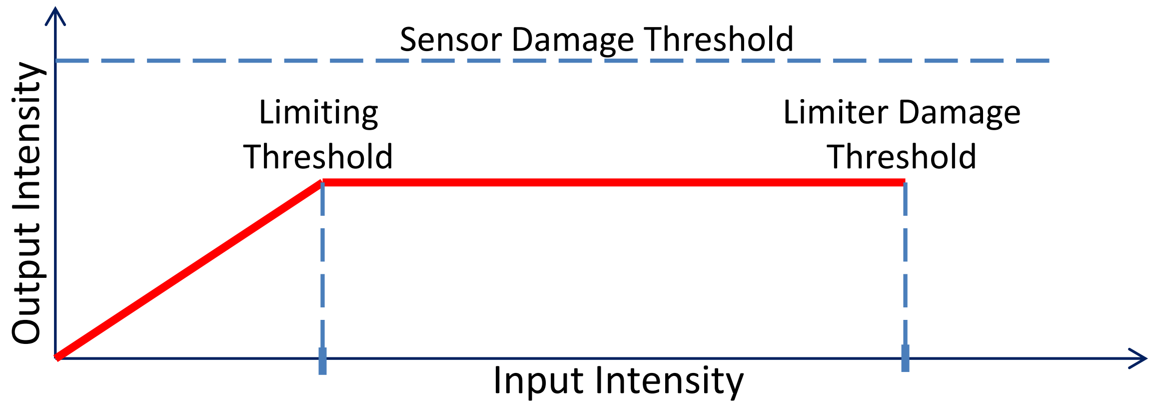


High intensity light is blocked

Transmitted light intensity vs. incident light intensity (schematic)



Two Figures of Merits

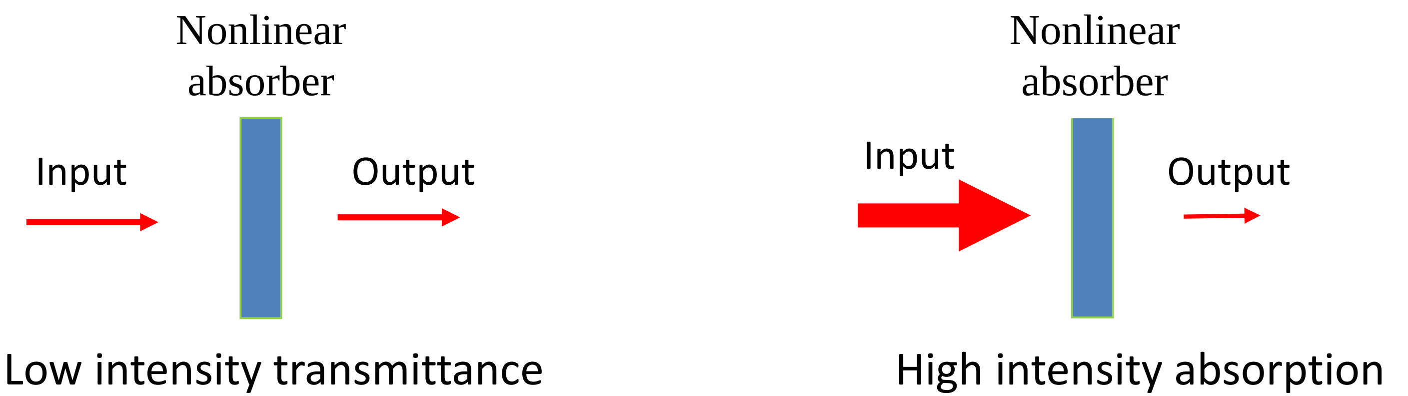


$$Extinction\ Ratio = \frac{Low\ Intensity\ Transmittance}{High\ Intensity Transmittance}$$

$$Dynamic\ Range\ = \frac{Limiter\ Damage\ Threshold}{Limiting\ Threshold}$$

In a sacrificial limiter: *Limiting Threshold = Limiter Damage Threshold*

A typical passive optical limiter is a thick enough layer of a material with low linear and strong nonlinear absorption



1. **At high input light intensity, nonlinear absorption can result in overheating and destruction of the limiter. The limiting threshold is usually close to the limiter damage threshold (a sacrificial limiter)**.
2. The extinction ratio achievable with optical materials with nonlinear absorption is often too low, which implies inadequate protection due to insufficient attenuation of the high-intensity input.
3. The limiting threshold provided by available optical materials with purely nonlinear absorption is often much higher than needed, which also implies inadequate protection.

Absorptive Optical Limiter / Switch

Low intensity transmittance

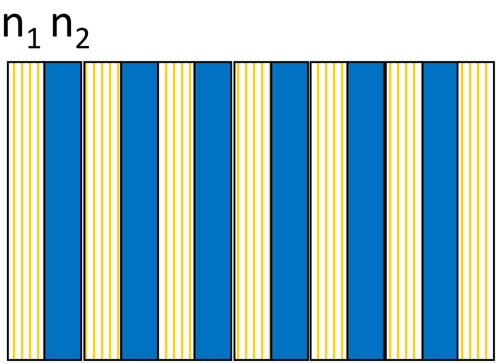
High intensity absorption

Reflective Optical Limiter / Switch

Low intensity transmittance

High intensity reflection

Simplest Realizations of a Reflective Photonic Limiter
(*found in the literature*)



First example

A PBG structure with matched linear refractive indices ($n_1 = n_2$). One of the two components displays strong Kerr nonlinearity. At high intensity, the periodic structure develops a narrow PBG and acts as a DBR.

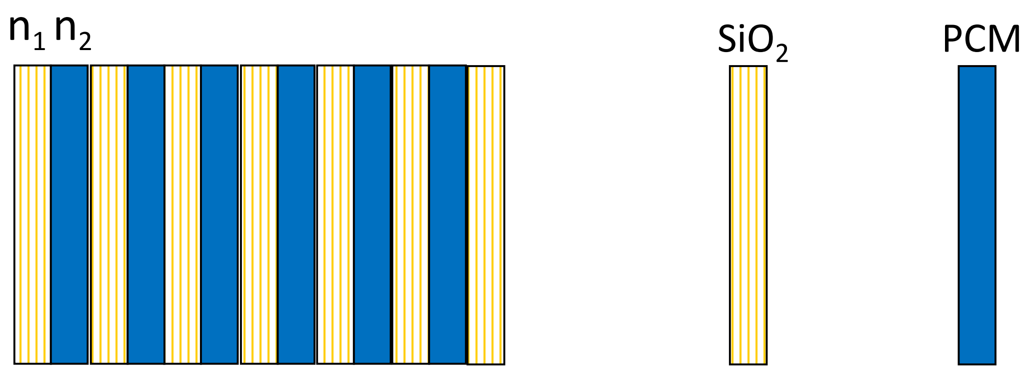
Second example

A PBG structure with $n_1 \neq n_2$. At high intensity, the photonic band edges shift, along with the transmission window.

Inherent problems with these (and similar) designs

1. Due to weakness of nonlinear refraction, such limiters can only provide a narrowband high-power reflectivity with a mediocre extinction ratio.
2. Direct exposure of vulnerable nonlinear material to high-level input radiation.
3. A rather messy transition from PASS state to BLOCK state.

To overcome the weakness of NL effects, a regular NL optical material can be replaced with a phase-changing material (PCM)



In our experimental realization*, PCM here is $Ge_2Sb_2Te_5$ (abbreviated as GST).

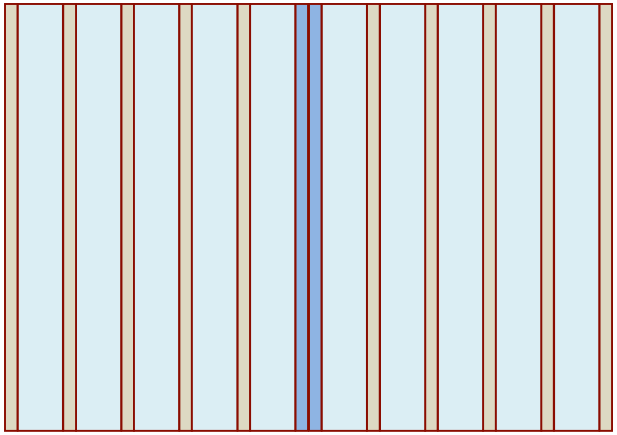
In the PASS state (below the GST phase change temperature), the transmittance greater than 80% was achieved at λ = 1500nm over a 300nm spectral width. In the BLOCK (reflective) state (above the GST phase change temperature), the extinction ratios higher than 30dB was achieved.

The remaining problems are: (i) direct exposure of the PCM to high-intensity input and (ii) rather messy transition from PASS state to BLOCK state.

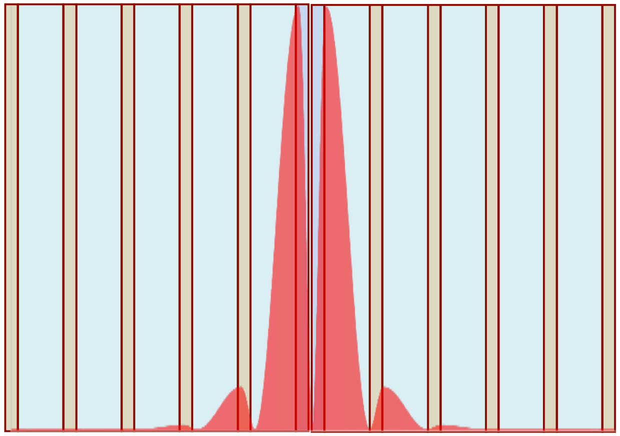
*A. Sarangan, J. Duran, V. Vasilyev, N. Limberopoulos, I. Vitebskiy, I. Anisimov. *Broadband Reflective Optical Limiter Based on GST Phase Change Material*. To appear in IEEE Photonics (Jan. 2018).

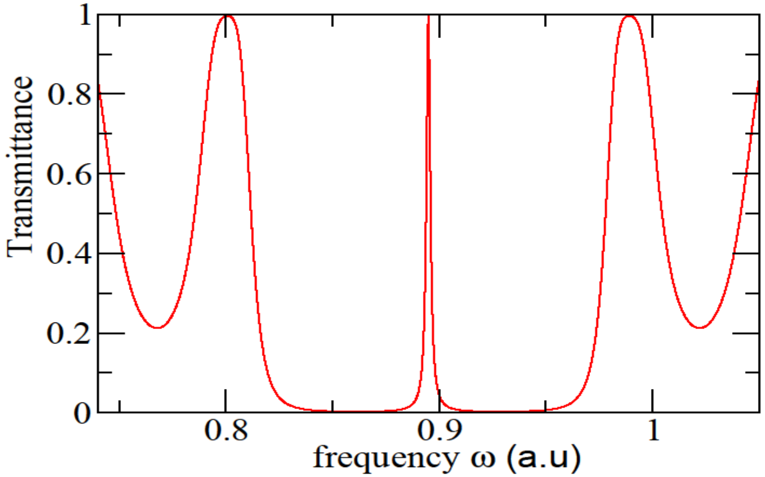
Reflective optical limiters based on nonlinear resonant cavity

Resonant cavity



Localized (cavity) mode





Resonant transmittance via localized (defect) mode

The question: *How to make the resonant transmittance go away (not just shift) at high input light intensity*?

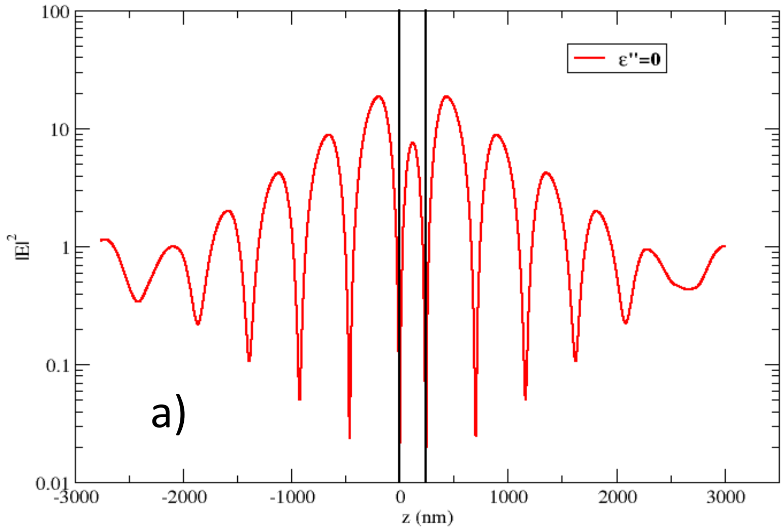
1) Symmetric resonant cavity with purely nonlinear absorption [1 - 6].
   In this case, at high intensity, the localized mode is suppressed (overdamped), along with the resonant transmittance.

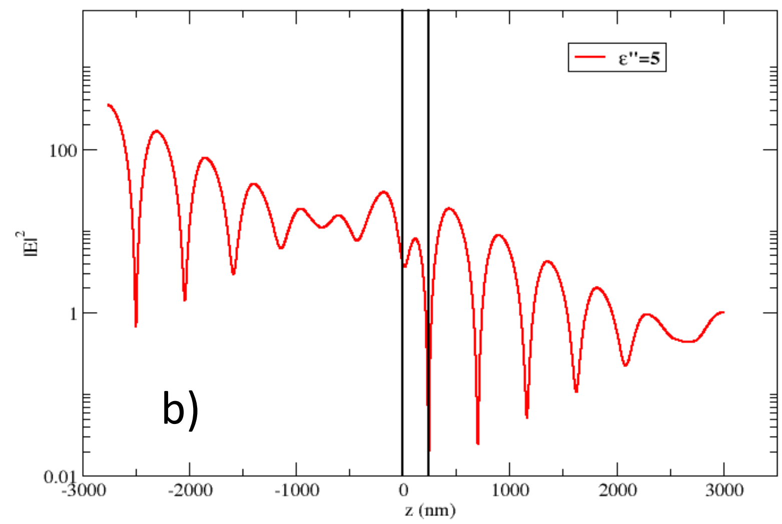
2) Asymmetric coupled resonant cavities with nonlinear components [11].
   In this case even a small nonlinear change in the refractive index decouples the incident light from the cavity mode, thus eliminating the resonant transmittance.

3) Asymmetric metal-dielectric resonant cavity with accidental degeneracy [3].

The limiting threshold of asymmetric cavity for the forward propagating light is different from that for the backward propagating light. The difference can be orders of magnitude! Particularly so if instead of common nonlinear optical materials we use phase changing optical materials [9, 12].

Shielding of the nonlinear layer from laser induced damage





Field distribution inside the layered structure at transmission resonance frequency:

a) Well-defined localized mode for low-level input. In the vicinity of the defect layer, the field intensity is exponentially higher than that of the incident wave. This results in lowering of the Limiting Threshold.

b) At high-level input , the localized mode is suppressed. The field intensity in the vicinity of the nonlinear defect layer, is exponentially smaller than that of the incident wave (the shielding effect). This results in a dramatic increase of the Limiter Damage Threshold.

Publications on the subject:

1. E. Makri, H. Ramezani, I. Vitebskiy, and T. Kottos. *Concept of a reflective power limiter based on nonlinear localized modes***.** Phys. Rev. A**89**, 031802 (2014).
2. E. Makri, I. Vitebskiy, T. Kottos. *Reflective optical limiter based on resonant transmission***.** Phys. Rev. **A91**, 043838 (2015).
3. E. Makri, K. Smith, A. Chabanov, I. Vitebskiy, T. Kottos. *Hypersensitive Transport in Photonic Crystals with Accidental Spatial Degeneracies*. Scientific Reports **6**, 22169 (2016)
4. U. Kuhl, F. Mortessagne, E. Makri, I. Vitebskiy, T. Kottos. *Waveguide Photonic limiters based on topologically protected resonant modes*. Phys. Rev. **B95**, 121409(**R**) (2017).
5. J. Vella, J. Goldsmith, A. Browning, N. Limberopoulos, I. Vitebskiy, E. Makri, T. Kottos. *Experimental realization of a reflective optical limiter*. Phys. Rev. Appl. **5**, 064010 (2016)
6. R. Thomas, I. Vitebskiy, T. Kottos. *Resonant cavities with phase-changing materials*. Optics Letters **42**, 4784 (2017)
7. R. Thomas, F. M. Ellis, I. Vitebskiy, T. Kottos. *Self-Regulated Transport in Photonic Crystals with Phase-Changing Defects*. Phys. Rev. A97, 013804 (2018).
8. R. Kononchuk, A. Chabanov, M. Hilario, B. Jawdat, B. Hoff, V. Vasilyev, N. Limberopoulos, I. Vitebskiy. *Reflective Photonic Limiter for the W-band.* Metamaterials, Marseille (2017)
9. N. Antonellis, R. Thomas, M. Kats, I. Vitebskiy, T. Kottos. *Asymmetric Transmission in Photonic Structures with Phase-Change Components*. Under review (2018)
10. A. Sarangan, J. Duran, V. Vasilyev, N. Limberopoulos, I. Vitebskiy, I. Anisimov. *A Broadband Reflective Optical Limiter Based on GST Phase Change Material*. To appear in IEEE Photonics (2018).
11. R. Kononchuk, N. Limberopoulos, I. Anisimov, I. Vitebskiy, A. Chabanov. *Photonic limiters with enhanced dynamic range*. SPIE (2018)
12. R. Kononchuk, N. Limberopoulos, I. Anisimov, I. Vitebskiy, A. Chabanov. *Nonlinear transmission via asymmetric array of resonant cavities*. Manuscript in preparation (2018)

Thank You