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Bidirectional-pump-controlled reconfigurable nonlinear spoof plasmonic waveguide

Key words: Nonlinear spoof surface plasmon polariton (SSPP); Phase-matching; Coherent perfect absorption (CPA); Perfect transmission

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Motivation

1. Traditional tunable absorbers often rely on modifying the physical parameters of materials or adjusting the phase difference between counter-propagating coherent waves, making it challenging to achieve bidirectional, dynamic, and efficient switching between absorption and transmission.

2. Existing nonlinear coherent absorption schemes are often limited by the pump incident direction and lack bidirectional control.

3. There is an urgent need for a device that can dynamically switch between perfect absorption and perfect transmission under both forward and backward pumping, to improve system flexibility and expand functional integration capabilities.

Main idea

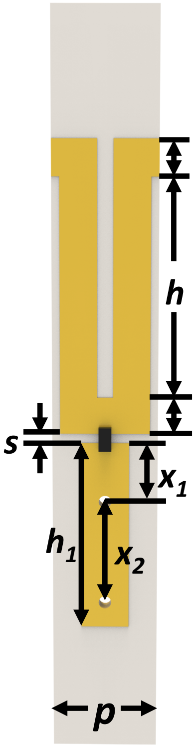
1. We propose a reconfigurable device based on an SSPP waveguide. It utilizes integrated varactor diodes to provide nonlinearity, and its dispersion is engineered to contain degenerate phase-matching points.

2. By leveraging the degenerate three-wave mixing mechanism under phase-matching conditions, the interference between the signal and idler waves is controlled, enabling a continuous transition from destructive to constructive interference and thus realizing dynamic tuning of the signal wave between coherent perfect absorption and perfect transmission.

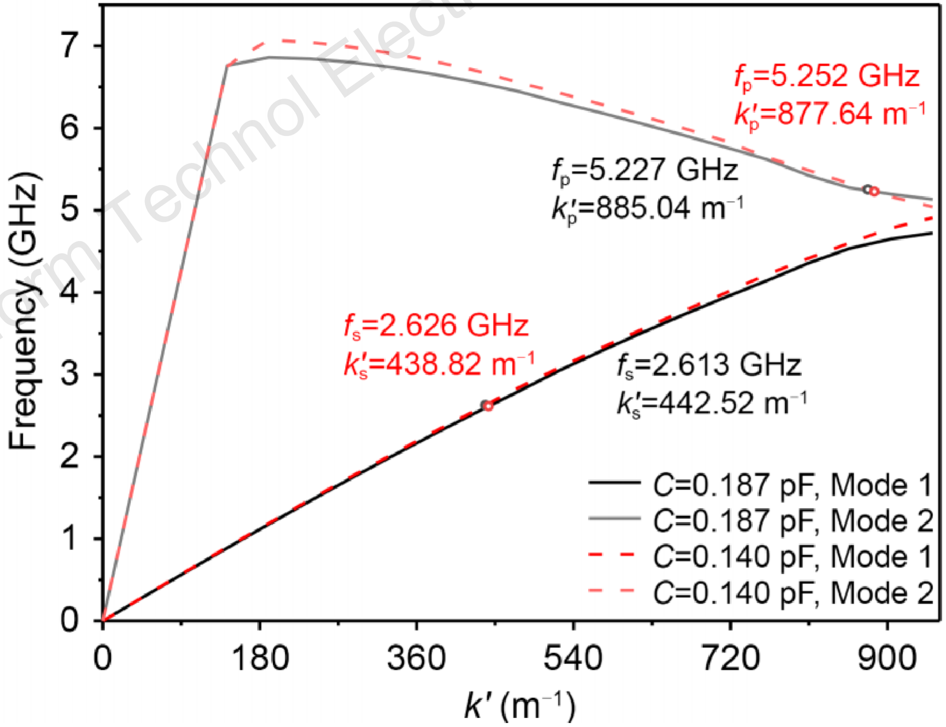
3. The device supports bidirectional pump injection, breaking through the traditional limitation of unidirectional control and enabling bidirectional signal amplitude modulation at both the transmitter and receiver ends.

Method

1. Structure Design & Dispersion Engineering: An SSPP unit integrated with nonlinear varactor diodes is designed so that its dispersion contains phase-matching points satisfying the degenerate conditions $f_p = 2f_s$ and $k_p^{'} = 2k_s^{'}$. Crucially, the positions of the phase-matching points are not sensitive to the varactor diode capacitance *C*, ensuring strong robustness.



SSPP unit structure

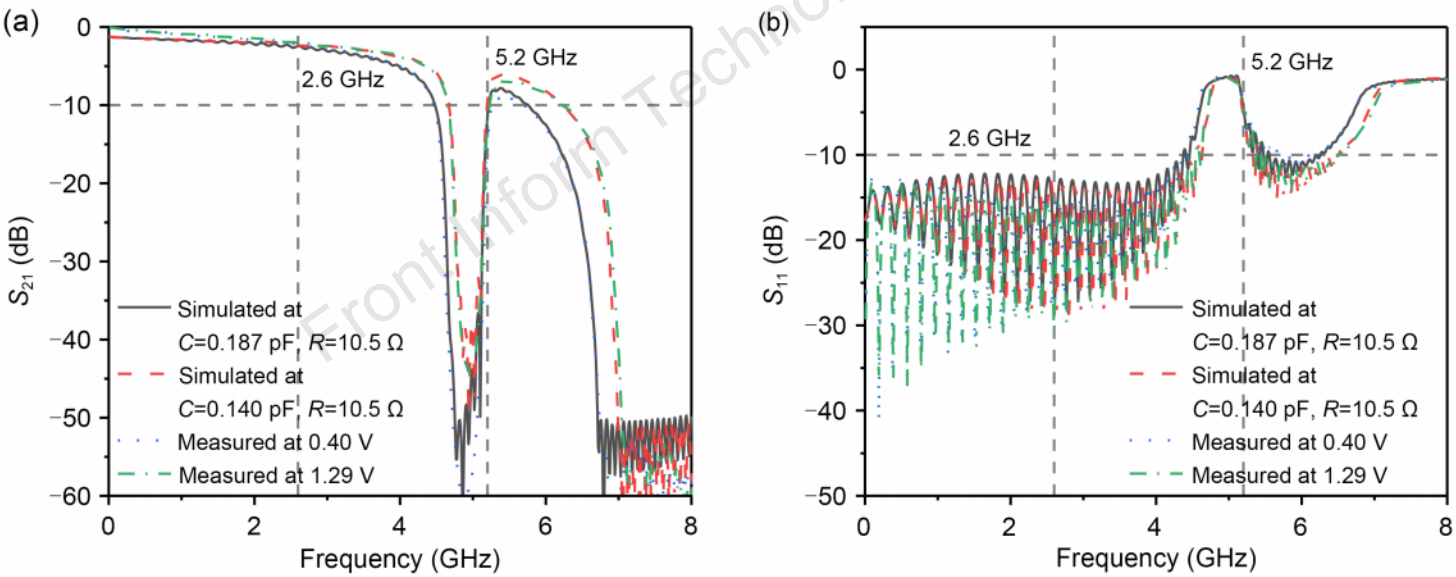


Simulated dispersion characteristics of the SSPP with varactor diode capacitances *C*=0.187 pF and *C*=0.140 pF

Method

2. Transmission & Reflection Coefficient Design:

- Signal Wave (2.6 GHz): Achieves high transmission and low reflection.
- Pump Wave (5.2 GHz): Designed with moderate transmission loss ($S_{21} \approx$ -12 dB) and high reflection ($S_{11} >$ -5.3 dB). This unique S-parameter profile ensures that the pump wave sustains both forward-propagating and strong backward-reflected components within the waveguide.



S-parameters of the 30-unit nonlinear SSPP waveguide: (a) transmission coefficient curves; (b) reflection coefficient curves

Method

3. Phase Control Mechanism:

- Derived from the three-wave mixing equations under the degenerate condition, the phase difference between the idler and signal waves is governed by the input phases:

$$\varphi_i - \varphi_s = (\varphi_p - 2\varphi_s) + 90^\circ - \arg(k_s)$$

- By tuning the phase difference between the pump and signal waves, $\Delta\varphi = \varphi_p - 2\varphi_s - \arg(k_s)$, we can directly control the interference between the generated idler wave and the signal wave:
  - I. At $\Delta\varphi = -90^\circ$, $\varphi_i - \varphi_s = 0^\circ$, **constructive interference**

    ↓

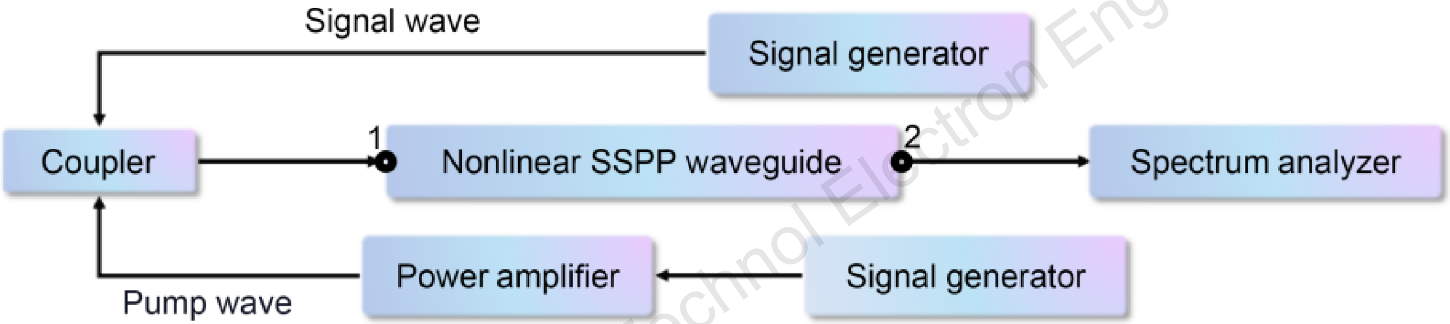
    maximum signal gain (perfect transmission)
  - II. At $\Delta\varphi = 90^\circ$, $\varphi_i - \varphi_s = 180^\circ$, **destructive interference**

    ↓

    minimum signal gain (coherent perfect absorption)

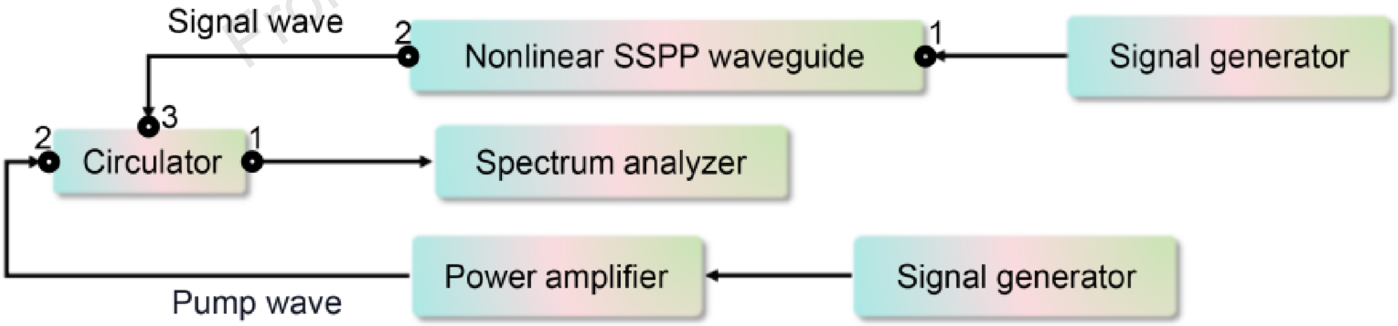
Method

4. Bidirectional Pumping Experiment: Forward/backward pumping setups are constructed, with interference between signal and idler waves controlled by tuning the input wave phase difference $\Delta\varphi$.



Signal wave
Signal generator
Coupler
1
Nonlinear SSPP waveguide
2
Spectrum analyzer
Power amplifier
Signal generator
Pump wave

Experimental setup with forward pump wave incidence

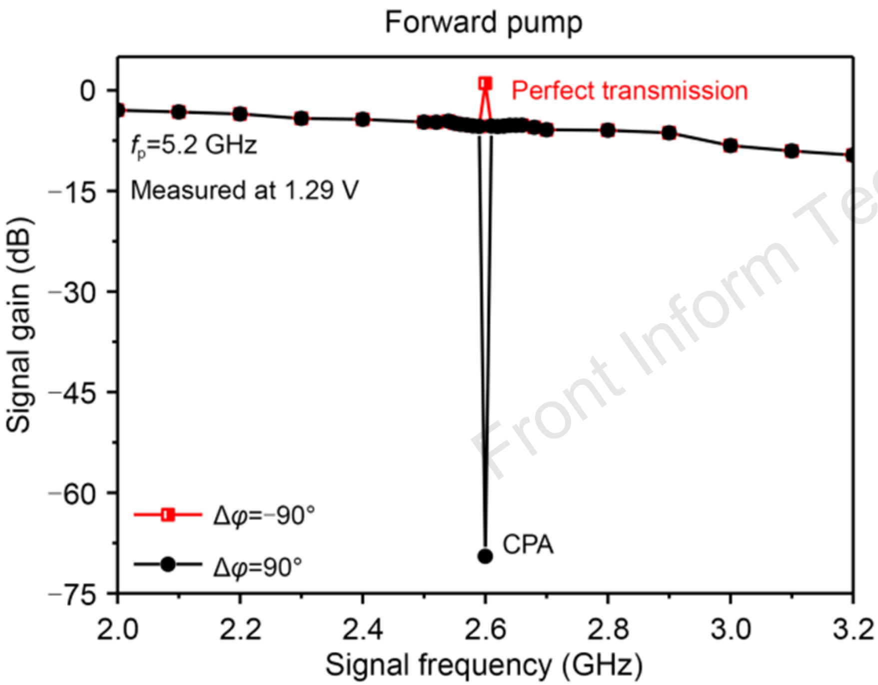


Signal wave
2
Nonlinear SSPP waveguide
1
Signal generator
3
2
Circulator
1
Spectrum analyzer
Power amplifier
Signal generator
Pump wave

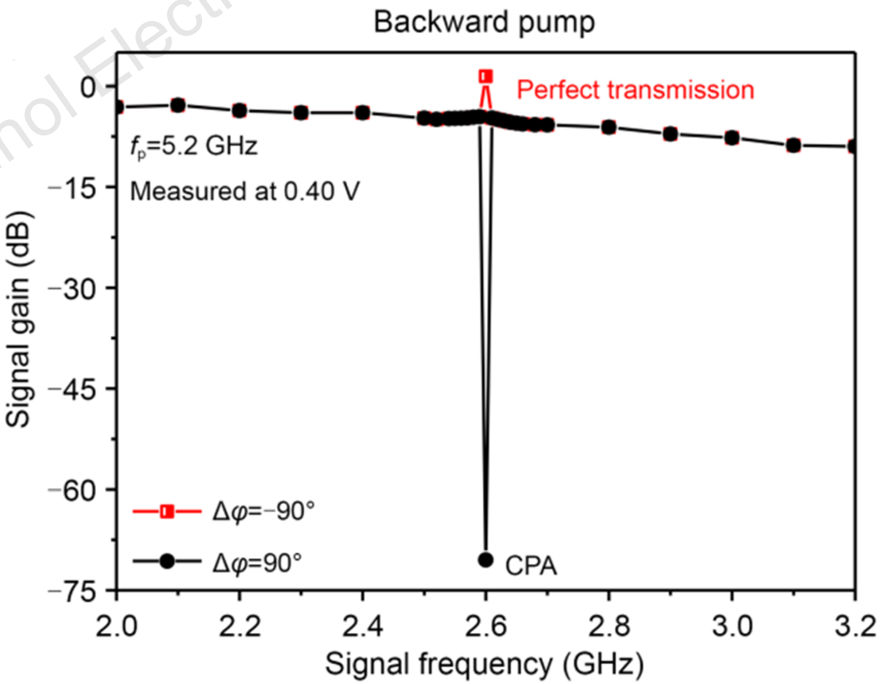
Experimental setup with backward pump wave incidence

Major results

1. Signal gain versus signal frequency: Coherent interference between the idler and signal waves occurs only when their frequencies are equal. Consequently, with the pump frequency fixed at 5.2 GHz, significant tuning of the signal gain via the input phase difference $\Delta\varphi$ is observed exclusively at the signal frequency of 2.6 GHz.



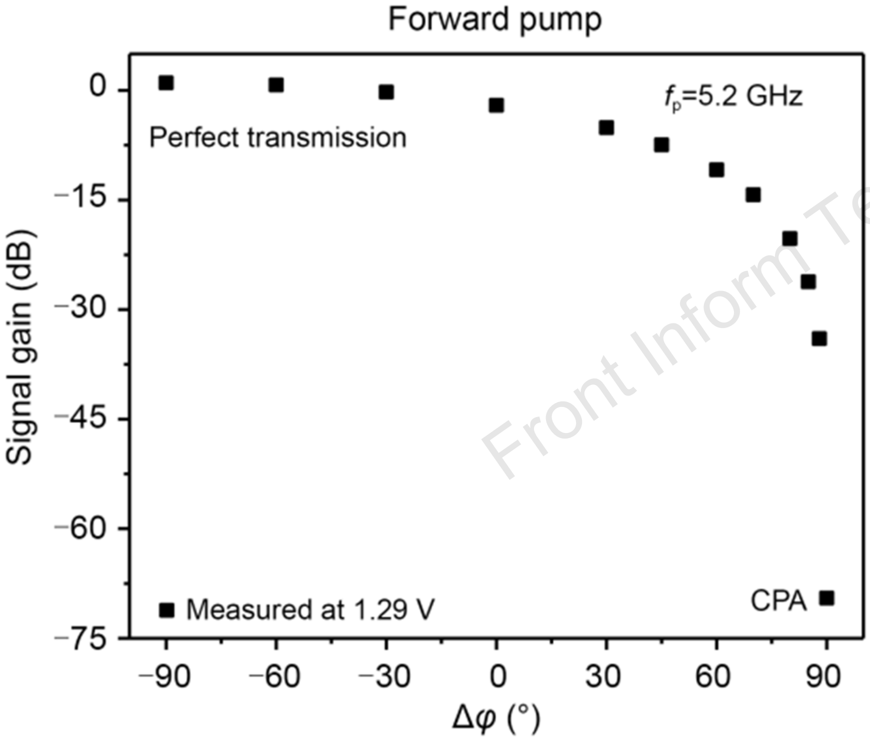
Signal gain versus signal frequency under forward pump wave incidence



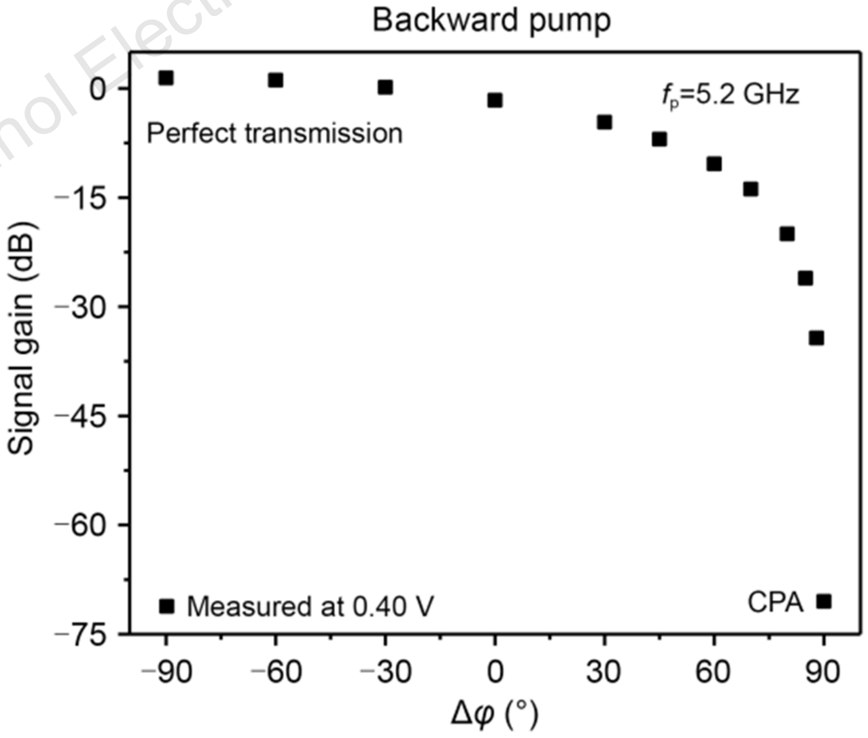
Signal gain versus signal frequency under backward pump wave incidence

Major results

2. Signal gain versus input wave phase difference Δφ: By adjusting the phase difference Δφ between the input pump and signal waves, the interference between the idler and signal waves can be controlled, enabling continuous tuning of the signal gain between its maximum and minimum values.



Signal gain versus Δφ under forward pump wave incidence



Signal gain versus Δφ under backward pump wave incidence

Conclusions

1. Innovative Design: A bidirectionally pump-controllable, nonlinear reconfigurable SSPP waveguide has been successfully realized. It is enabled by its dispersion design with robustness against capacitance drift and unique *S*-parameter co-design, which collectively ensure stable satisfaction of the degenerate phase-matching condition under both forward and backward pumping.

2. Outstanding Performance: Experiments demonstrate that at the 2.6 GHz signal frequency, the device can continuously and dynamically tune the signal gain from <-69.5 dB (Coherent Perfect Absorption) to >+1 dB (Perfect Transmission) by adjusting the pump phase, achieving a dynamic range exceeding 70 dB and an absorption efficiency greater than 98.7%.

3. Breakthrough & Application: This work breaks the unidirectionality limitation of traditional coherent control, providing a new device paradigm for adaptive energy harvesting, reconfigurable signal processing, and coherent microwave systems.

Author biographies

Jingjing ZHANG received her Ph.D. degree from Zhejiang University, China in 2009. She has been an H. C. Ørsted Postdoctoral Fellow and assistant professor at Technical University of Denmark, Denmark, a Newton International Fellow at King's College London, UK, and a senior research fellow at Nanyang Technological University, Singapore. Currently, she is a professor at State Key Laboratory of Millimeter Waves, Southeast University, China. Her research interests include metamaterials, nanoplasmonics, and designer surface plasmons.

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