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# Surface plasmon polariton boosted photorefractive scattering in indium tin oxide coated Fe-doped lithium niobate slabs

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## ABSTRACT

To study the impact of surface plasmon polaritons on photorefractive effect, indium tin oxide (ITO) thin films were deposited onto Fe-doped lithium niobate (Fe: $LiNbO_3$, LN) slabs. Striking scattering near surface normal (SNSN) of the slabs was observed, increasing with the incident angle of laser beam. The SNSN was so strong that it depleted the transmitted beam. Based on a tentative physical picture of photovoltaic (PV) effect induced electrostatic modification, the electron density of skin layer of ITO film was raised to such a level that surface plasmon polaritons (SPPs) were excited in LN/ITO interface via phase grating mediation. Consequently, the localized intensified electromagnetic fields exerted on the LN slabs and resulted in the SNSN. The impact of the SPPs and SNSN on the photorefractive effect can be seen from over 2.5 times SNSN enhancement in power and as high as 6.0 times boosting of the ratio of the SNSN power to the remaining transmitted one.

## 1. Introduction

The proliferation in nanoscale science and technology research has propelled the development of a variety of promising devices and led to blossoming multidisciplinary plasmonics research. Since electromagnetic (EM) fields associated with the surface plasmons are localized at interfaces of conductor and dielectric layers and are often intensified greatly [1,2], the nonlinear optical response of the dielectric layer adjacent to the conductor should be boosted tremendously [3]. Plasmonics has also been used in the semiconductor device, such as solar cells, nanolasers, integrated circuits, LEDs and so on [4–7]. In the past years, the well conductive n-type degenerate semiconductor indium tin oxide (ITO) thin films attracted growing attention to meet the needs in infrared (IR) plasmonics [8–14]. Compared with metal materials, the ITO semiconductor family and similar others possess relatively low charge carrier density and hence are regarded as ideal materials for IR plasmonics [8,9]. Since plasma frequency of conductor is mainly dictated by electron density, if the effective electron density of ITO thin film is altered by introducing extra electrons by means of electrostatic modification or other ways of charge injection, and then the response can be pushed towards short waves. Lithium noibate ($LiNbO_3$, LN) synthetic crystals are known for their PV effect, especially when doped with transition metal iron or rare earth cerium elements. When a Fe doped LN slab is coated with ITO film, a great number of PV charge carriers can be injected into the skin layer of ITO film. As the result, plasma frequency of ITO layer can be raised greatly. When phase gratings are written in the excellent photorefractive LN slab, surface plasmon polaritons (SPPs) can be excited via mediation of those phase gratings. The SPPs thus excited can localize EM fields in a thin layer of sub-wavelength and hence intensify the EM fields. The intensified EM fields in the nonlinear LN layer would no doubt result in strong new phenomena. Another reason for choosing LN crystals since they are among the most investigated and used nonlinear optical materials [15], and have drawn growing attention recently associated with harmonic generation [16], production of photonic crystal structure [17], high-Q optical whispering-gallery-mode resonances, optical parametric oscillators, and other interesting phenomena [18–21]. The combination of ITO and LN is meant to take advantage of in-depth knowledge of the “silicon in photonics” and low plasmonic loss of ITO. When we investigated the optical nonlinearity of the ITO-coated LN slabs, striking scattering near the surface normal (SNSN) was observed, hinting that SPPs were excited near the LN/ITO interface and responsible for generating SNSN. The SNSN was so strong that it depleted the transmitted beam. Based on a tentative physical picture of PV effect induced electrostatic modification, the electron density of skin layer of ITO film was raised to such a level that SPPs were excited in LN/ITO interface via phase grating mediation. Consequently, the localized intensified electromagnetic fields exerted on the LN slabs and resulted in the SNSN cone. The impact of the SPPs and SNSN on the

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photorefractive effect was discussed further by performing more experiments. This study itself deserves further investigation for a potential broad spectrum of applications, since the nonlinear optical core material can be replaced by other materials, such as polymeric, liquid crystalline, ceramic form materials. We report our works as follows.

## 2. Experimental and analysis

All the LN crystal slabs were doped with 0.1 wt% $Fe_2O_3$, grown by conventional Czochralski method from the congruent melt chosen as Li/Nb=48.6/51.4, detailed description can be found in Ref. [22]. The slabs were cut from an as-grown LN single crystal slug, and their dimensions were $0.2 \times 10.0 \times 12.0\ \text{mm}^3$ with a pair of opposite surfaces ($10.0 \times 12.0\ \text{mm}^2$) optically polished, besides optical axis was parallel to the polished surfaces, known as *y*-cut slabs. All the slabs were coated with 150-nm thick ITO films on both the polished surfaces. A continuous diode pumped solid state green laser (532 nm) (Cobolt Samba 100) was used as the coherent light source. As shown in Fig. 1(a), both the extraordinary polarization incident light and the *c*-axis of the ITO coated LN slab were parallel with the horizontal plane. The incident laser beam was focused by a lens ($R=10$ cm) when illuminating the sample which was placed at the center of a rotary stage. After the stray light was blocked by the iris, the SNSN power and the transmitted power were measured by optical power meter (THORLABS S120VC, PM100D).

In the thin ITO coated Fe doped LN slabs, strong large angle scattering near the slabs' edges was observed and this was proposed previously as the origin of the enhancement of the energy transfer from the pumping to signal beams [23]. In addition to the large angle scattering, in this work, it was found that a very strong scattering near surface normal (SNSN) light cone with the identical polarization to the incident laser beam developed rapidly, and dominated eventually in power when the slab was slanted (refer to Fig. 1(a) and (b)). The SNSN light cone emitting from the ITO-coated slab was brighter when the incident laser beam was focused by a lens. In the experiments, an ITO-coated slab was slanted at $\theta=60°$, the incident laser power was 63.5 mW and the beam diameter 0.4 mm. The direct transmitted light was 31.6 mW, measured immediately after the incident light illuminating the slab. However, the directly transmitted light dropped in power very quickly and settled down at 4.7 mW. Meanwhile, the SNSN cone gained power from 0.2 μW up to 31.2 mW, and the final reflection power settled down at 3.8 mW. This means that apart from the energy absorbed by the slab, near 78.6% visible light energy exited as the SNSN cone. In comparison, only 21.6% light energy was transferred into the SNSN portion in the best case with an uncoated LN slab. Generally, the total SNSN power increased with the slanted angle. For the same incident power 63.5 mW, the angular dependences of the SNSN power on the slanted angle in two slabs are exhibited in Fig. 1(c), and the typical SNSN dynamic curves taken at $\theta=50°$ are shown in Fig. 1(d). One can see that even at relatively small slanted angle (20–40°), the SNSN portions were quite high in the ITO slab, whereas no appreciable SNSN light was seen in the uncoated slab. Starting at 14 mW at $\theta=20°$ in the ITO-coated slabs, the SNSN power increased almost linearly with increasing incident power (see the solid line in Fig. 1(c)). However, the SNSN power from the uncoated LN slab at 20° and 30° slanted angles were only 0.1 and 1.5 mW, respectively. Nevertheless, the SNSN power from the uncoated slab developed nearly

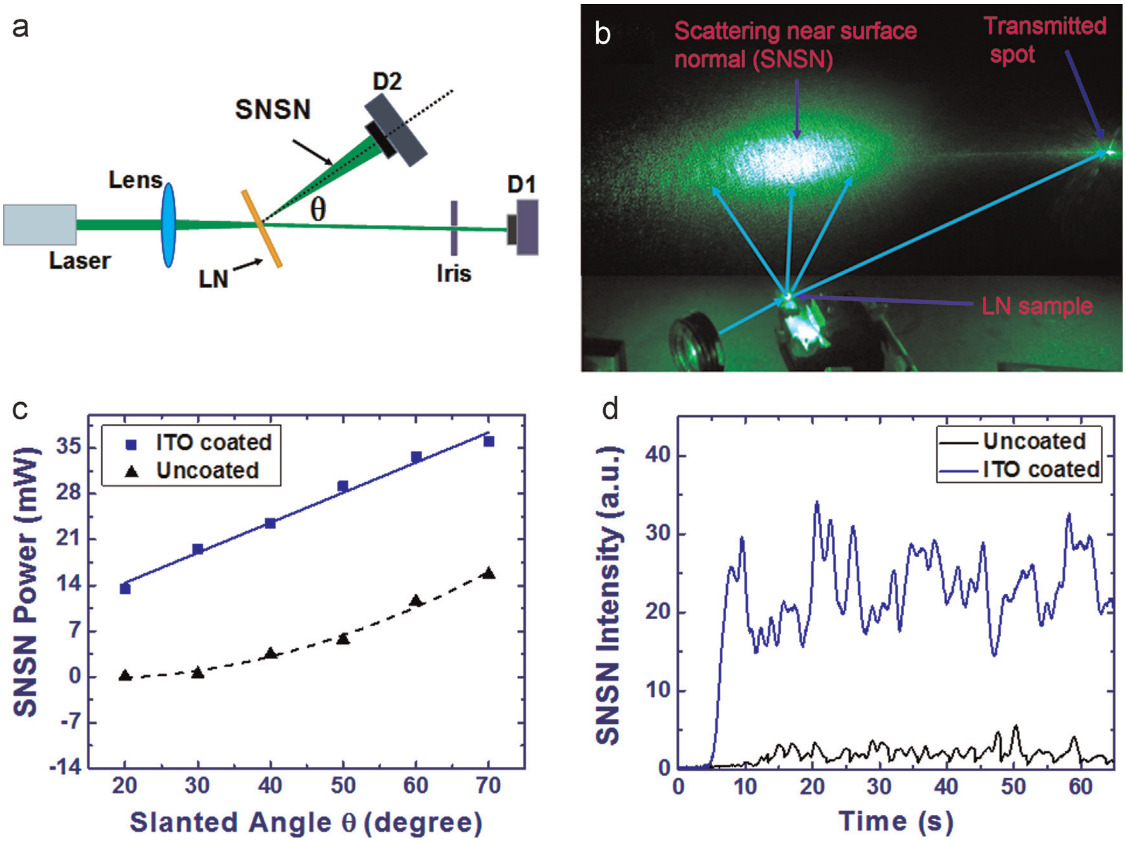

**Fig. 1.** Experimental scheme and dynamics of SNSN. (a) Experimental scheme of observing the SNSN and directly transmitted laser light; (b) a photograph taken to show the geometry illustrated in (a); (c) the SNSN power dependences on slanted angle in uncoated and ITO-coated LN slabs; (d) typical SNSN dynamics obtained in the two slabs used.