other higher ordered guided modes. However, different from the small field overlap of those higher ordered modes that commonly leads to low conversion efficiency, the field overlap of SPP and TM_1 mode is acceptable [see Fig. 1(b)], which fortunately provides us the possibility to realize the direct phase matching condition without any additional structural design (like Ref. 22). In fact, other second order nonlinear effects between SPP and conventional waveguide mode also can be derived in such kind of nonlinear hybrid waveguide. For example, the reversed process of this OPA, i.e., second harmonic generation from the SPP to the double-frequency waveguide mode, is reasonably expected as long as the phase matching condition is satisfied. Therefore, this scheme provides a new way not only to achieve the frequency conversions but also to realize the switches between the conventional guide wave and subwavelength SPP wave. From this point of view, such a hybrid waveguide also can be regarded as a coupler from radiative light to evanescent wave and vice versa.

Nevertheless, the revealed SPP amplification is still an important application of this nonlinear optical process. It may really provide opportunities to overcome the propagating loss of SPP rather than using a common gain medium. Furthermore, from our detailed analyses of the OPA influenced by the pumping intensity and phase tuning, this method reveals convenient modulations on the SPP wave at will, but not a merely amplification. In this sense, information can be loaded on the pumping guided wave to control SPP behavior, which is considered very important in future subwavelength integration and modulations.

5. Conclusion

In summary, a new method is proposed to realize an optical parametric amplification for an SPP wave in nonlinear hybrid waveguide. Taking advantage of the different dispersion of SPP mode and conventional guided wave, we desirably obtain the phase matching condition between these two modes, which is of vital importance for the nonlinear optical parametric process. Our results definitely indicate that with the aid of auxiliary pumping wave (TM_1 mode) the SPP wave can be loss-compensated and even amplified to a high level as the pumping energy is large enough. It surely suggests possible applications as subwavelength waveguide that overcome the usual propagating loss. According to our detailed investigations, the OPA efficiency and process are found closely related with intensity of the pumping guided wave and its initial phase with respect to that of SPP. This phase tuning notably provides a tunable modulation method potentially in the future subwavelength optical integrations.

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