Effective Periodic Poling in Optical Fibers

Jongbae Kim, Jung Jin Ju, Min-su Kim, and Hong-Seok Seo

ABSTRACT—The distributions of electric field and induced second-order nonlinearity are analyzed in the periodic poling of optical fibers. A quasi-phase matching efficiency for the induced nonlinearity is calculated in terms of both the electrode separation distance between the applied voltage and generalized electrode width for the periodic poling. Our analysis of the quasi-phase matching efficiency implies that the conversion efficiency can be enhanced through adjusting the separation distance, and the electrode width can be maximized if the electrode width is optimized.

Keywords—Periodic poling, quasi-phase matching efficiency, optical fiber, distributions of electric field, induced second-order nonlinearity.

I. Introduction

For more than a decade, the induction of second-order nonlinear phenomena and the enhancement of conversion efficiency in silica fibers have been attractive concerns for the application of such fibers in optical communications. Due to the centrosymmetric structure of silica, which a priori implies the absence of the second-order nonlinear effect in silica fibers, a poling technique was introduced [1]. In flat poling (uniform poling), ultraviolet exposure was simultaneously applied to a twin-hole fiber to induce a higher nonlinearity [2], while in periodic poling, lithography patterning was explored in a D-shape fiber to obtain higher second-harmonic generation (SHG) [3] by means of quasi-phase matching (QPM) [4]. The exact origin of the nonlinearity induction in the silica by the poling is not known yet, but the induced nonlinearity is known to possess a linear relationship with the strength of an applied electric field [5].

In periodic poling, it is believed that not only the absolute magnitude of the nonlinearity but also its distribution to fit the required QPM condition make crucial contributions to conversion efficiency. In the conventional fabrication of periodic electrodes for QPM in the D-shape fiber, half of a QPM period is normally in contact with a designed electrode, but the remaining half period is devoid of the electrode so as to yield a +/0 distribution of the electric field and of the consequent nonlinearity. Regardless of such intension, assuming one half of the period is exposed to the constant electric field while the other half of the period is free from any field, the tailed field leaking out to the region outside of the periodic electrode is unavoidable. In a QPM point of view, the field leakage should be avoided because the leakage distribution of the induced nonlinearity is believed to damage QPM efficiency quite severely. Therefore, to enhance an effective second-order nonlinear coefficient, or equivalently the conversion efficiency, a precise-as-possible QPM fitted by the nonlinearity distribution is indispensable.

For the analytical study of QPM efficiency in the periodic poling, a theory was proposed based on a simplified modeling of the nonlinearity distribution induced by the electric field [6]. In following experimental tests of the model by polymer waveguides, which in fact confirmed the validity of the model, the converted power distributions measured in the SHG were in accordance with the theoretical prediction [7], [8], and the phenomenon of difference-frequency generation was observed [9]. In this study, based on the established theory and experimental confirmations, we analyze the induced nonlinearity distribution and discuss the QPM efficiency in the periodic poling of optical fibers.

II. Analysis and Results

As mentioned above, the highest conversion efficiency in the SHG of optical fibers was accomplished through the D-shape

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fiber that employed the +/0 poling scheme and adopted the same scale of the periodic electrode width and the coherent length defined as one half of the QPM period $(Lc \equiv \Lambda / 2)$ [3]. Based on the experimental situations, let's now consider the corresponding poling scheme where the periodic electrodes are placed in period intervals on one side while a continuous flat electrode (uniform electrode) is placed on the other side, as given in Fig. 1.

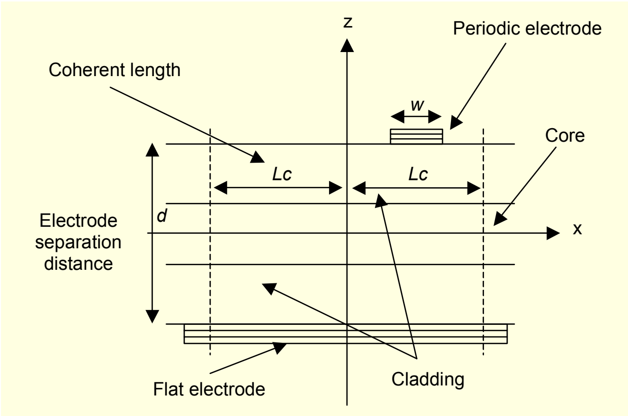

Fig. 1. The simplified side view of a poling scheme.

As discussed in detail in [6], a basic distribution of electric field E_0 between a single periodic electrode centered at $x = Lc/2$, where the coordinate x is the propagation direction of light along the center of the core, and the flat electrode can be proposed as

$$E_0(x - \frac{Lc}{2}, w, 2d) \equiv \begin{cases} \dfrac{2dE_Q}{2x - Lc - w + 2d}, & (x \geq \dfrac{Lc}{2} + \dfrac{w}{2}) \\ E_Q, & (|x - \dfrac{Lc}{2}| \leq \dfrac{w}{2}) \\ \dfrac{2dE_Q}{-2x + Lc - w + 2d}, & (x < \dfrac{Lc}{2} - \dfrac{w}{2}). \end{cases} \quad (1)$$

Here, w is the generalized width $0 < w \leq Lc$ of the single QPM electrode, d is the electrode separation distance (fiber thickness) between the periodic electrode and the flat electrode where a potential difference is applied, and E_Q represents the simplified field strength. The field strength by definition should be constant and uniform between the periodic and flat electrodes, similar to the case of infinite planes. Since the QPM period is determined only by a QPM condition among the wave vectors of the coupling waves propagating in the core region and the field distribution in (1) is generated naively from the poling electrodes, which are irrelevant for waveguide geometry, the field distribution can be applicable directly to fiber geometry as well [6]. Due to the translation symmetry of the electrode structure, any period can be taken without loss of any generality, and the whole structure is nothing but a simple repetition of the single period. The basic field distribution then yields a total electric field if the potential difference is applied to the whole structure of the electrodes.

The total electric field is in fact a linear superposition of the electric field generated between the single QPM and the flat electrode in the period of interest and other fields tailed from the remaining regions outside of the period. After lengthy calculation, the total electric field results in

$$E_t(x, w, d) = E_0(x - \frac{Lc}{2}, w, 2d) + \sum_{n=1}^{n_R} \left[\frac{2dE_Q}{-2x + (4n+1)Lc - w + 2d} + \frac{2dE_Q}{2x + (4n-1)Lc - w + 2d} \right], \quad (2)$$

where n_R is the effective number of neighboring periods for the contribution. The total electric field will leave a poling effect on the optical fiber to induce the second-order nonlinear coefficient $d_2(x, w, d)$ according to the linear relationship, $d_2(x, w, d) \propto E_t(x, w, d)$. The physical characteristics of the induced coefficient can then be determined from the total field distribution.

In order to calculate an effective contribution of the coefficient to any nonlinear optical phenomenon, the QPM mean distribution of the nonlinear coefficient is defined as

$$< d_2(w, d) > \equiv \frac{1}{\Lambda} \left[\int_0^{\frac{\Lambda}{2}} d_2(x, w, d) dx - \int_{-\frac{\Lambda}{2}}^{0} d_2(x, w, d) dx \right] \quad (3)$$

in a period. In the case of the flat poling with a constant nonlinearity $d_2(x, w, d) = d_Q$ in the entire period, the mean distribution is null. However, in the case of the perfect QPM with $d_2(x, w, d) = d_Q$ in $0 < x \leq Lc$ and $d_2(x, w, d) = -d_Q$ in $-Lc \leq x \leq 0$, the mean distribution is $< d_2(w, d) > = d_Q$, which leads to 100% QPM efficiency. Based on (3), the QPM efficiency of the nonlinear coefficient is calculated to be

$$\frac{< d_2(w, d) >}{d_Q} = \frac{1}{2} \cdot [\frac{w}{Lc} + \frac{1}{2} \cdot \frac{2d}{Lc} \ln \frac{(Lc - w + 2d)^3}{(3Lc - w + 2d)(2d)^2}] + \frac{1}{4} \cdot \frac{2d}{Lc} \cdot \sum_{n=1}^{n_R} \ln \frac{[(4n-3)Lc - w + 2d][(4n+1)Lc - w + 2d]^3}{[(4n-1)Lc - w + 2d]^3 [(4n+3)Lc - w + 2d]} \quad (4)$$

in a dimensionless unit.

In Fig. 2, the two-dimensional plot of the QPM efficiency $< d_2(w,d) > / d_Q$ is illustrated in terms of the normalized electrode width *w/Lc* by dotted and solid lines corresponding to *d/Lc*=0.1, 0.3, 0.57, 1.0, 2.0, and 5.60 from the upper right corner down, in the case of $n_R=3$. The general behaviors of the distributions show that each of the efficiency lines increases as *w/Lc* decreases from 1, but they begin to decrease after each critical maximum point. Also, as the *d/Lc* values increase, the QPM efficiencies at *w/Lc*=1.0 become lower, the values of *w/Lc* where the critical maximum points exist tend to be shifted to the left, and the efficiency change for each *d/Lc* becomes smaller for each change of *w/Lc*. This implies that if the electrode width becomes shorter than the conventional coherent length, then both a region of the electrode width where the QPM efficiency is enhanced and an optimum of the electrode width where the QPM efficiency is maximized exist when compared with the efficiency at *w/Lc*=1.

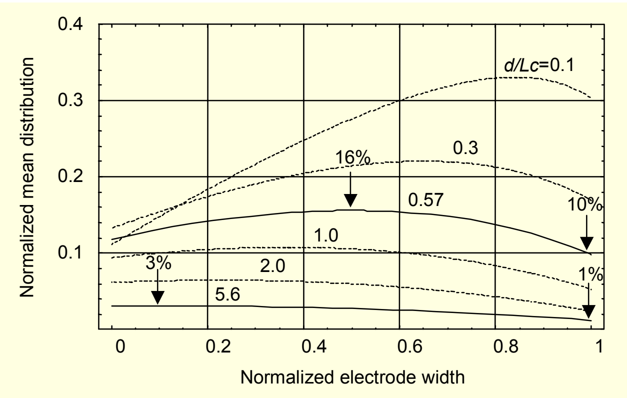

Fig. 2. A Two-dimensional plot of the QPM efficiency in terms of the normalized electrode width.

The most efficient SHG using the D-shape fiber was carried out with *d/Lc*=158 μm/28.225 μm=5.6 at the end point *w/Lc*=1.0, which resulted in the QPM efficiency of 1%, as shown by the lowest solid line in Fig. 2. In this case, the figure of merit (normalized efficiency) [10]

$$\eta_{FOM} \equiv \frac{P_{2\omega}}{P_\omega^2 L^2} \propto < d_2(w,d) >^2 \qquad (5)$$

defined in terms of the peak powers, as specified in [3], is 0.75 kW/(2.5 kW×7.5 cm)^2=2.13×10^{-4} %/Wcm^2. This figure of merit can be enhanced by a factor of 9 by dint of shortening the width of the periodic electrodes to the critical optimum *w/Lc*=0.1, which leads to a 3% efficiency. In the case of *d/Lc*=5.6, the QPM efficiencies are inevitably low because the electrode separation distance *d* is relatively so long when compared with the coherent length *Lc* that the leakage of the electric field strength outside of the electrode width becomes intensive.

However, the intrinsic enhancement of the QPM efficiency can be possible, as explicitly illustrated by the upper solid line of *d/Lc*=16 μm/28.225 μm=0.57, if, for example, the distance *d* can be shortened by making the round cladding part of the D-shape fiber flat enough to maintain 5 μm separations from the core edge to the two side surfaces or equivalently by a different geometry of the twin-hole fiber [11], as compared schematically in Fig. 3. The middle electrode in the left D-type fiber is the virtual one prepared for use in cases when the round cladding part is polished and flattened to make *d* shorter, while the two holes in the right twin-hole fiber are the ones fabricated to put the electrodes into the fiber. In this case, if all the conditions are assumed identical, the QPM efficiencies can be enhanced to 10% at *w/Lc*=1.0 and to 16% at *w/Lc*= 0.5, as shown by the upper solid curve in Fig. 2. As a result, at its optimum, the figure of merit increases up to (16%/1%)^2×2.13×10^{-4} %/Wcm^2=5.45×10^{-2} %/Wcm^2 and the effective nonlinear coefficient given by the average powers in [3] becomes $<d_2(w,d)>$ = (16%/1%)×0.014 pm/V = 0.224 pm/V.

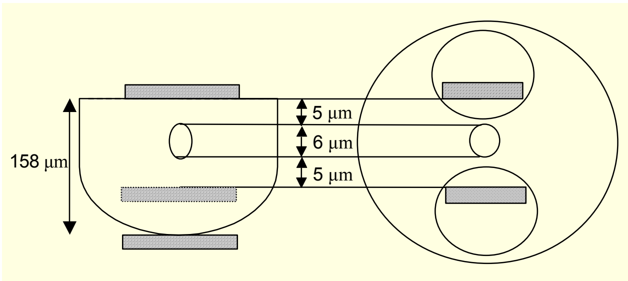

Fig. 3. A schematic comparison of a poling scheme between two types of fibers.

In Fig. 4, the normalized nonlinearity distributions $d_2(x,w,d)/d_Q$ induced from the field strength are plotted in terms of the normalized position *x/Lc* from top to bottom in cases where *w/Lc*=1.0 and 0.1 for *d/Lc*=5.6, and *w/Lc*=1.0 and 0.5 for *d/Lc*=0.57, respectively, under $n_R=3$. Each distribution is on the whole plane in the QPM electrode region centered at position *x/Lc*=1/2 with the given width, but each makes a smooth dip in the remaining region of the period. In the case of a large *d*, the field leakage outside of the QPM electrode region increases as given in (1), (2). Hence, the two upper lines show a seemingly larger magnitude of distributions when compared with the two lower lines due to the larger leakage fields tailed from the effective neighboring electrodes. In spite of such larger inductions, the distributions imply almost no difference in the regions $-1 \le x/Lc < 0$ and $0 \le x/Lc < 1$. Therefore the QPM efficiencies are low according to the definition in (3). The two lower distributions, however, show better behaviors in view of the QPM distribution and thus lead to the enhanced efficiencies, as indicated by the upper solid line in Fig. 2.

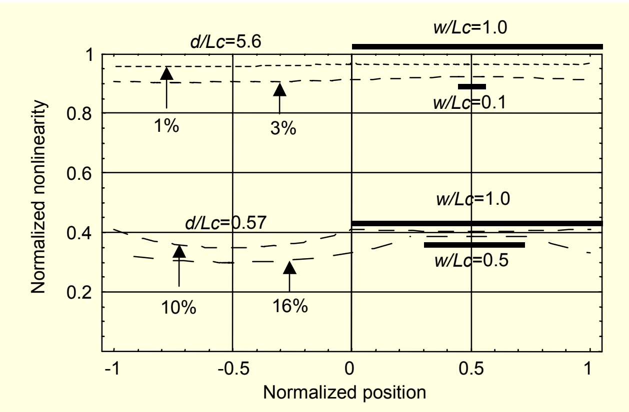

Fig. 4. Normalized nonlinearity distributions in terms of the normalized position.

III. Conclusions

The distributions of electric field and induced nonlinearity in the periodic poling of optical fibers are derived. Through the theoretical analysis of quasi-phase matching efficiency, we suggest a new poling scheme for optimizing the electrode width to maximize the conversion efficiency in future experiments. Our poling scheme can be applied to a twin-hole fiber and other relevant nonlinear devices.

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