Simulation of field-assisted ion-migration process for glass-based PLC fabrication: influence of joule heat effect

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In field-assisted ion-migration (FAIM) process conventionally employed for glass-based planar lightwave circuit (PLC) devices fabrication, glass wafer temperature rise induced by Joule heat effect influent this process profoundly. In this context, obtaining glass temperature rising behavior comprehensively is of great importance. Based on thermal balance equation, simulation of glass wafer temperature rising behavior is carried respectively on for FAIM process in CV regime, CC regime, and CV-CC regime as well. Results show that glass wafer temperature rising behavior can be obtained with high efficiency and reasonable accuracy. Analysis demonstrate that this approach gives significant insight into phenomena related to Joule heat effects, it can also provide a practical tool for design and fabrication of glass-based PLC devices.

1. Introduction

Planar lightwave circuit (PLC) devices in glass substrate fabricated by ion-exchange technology possess many distinguishing merits, including optical compatibility with optical fiber, suitability for mass production, and unique cost-effectiveness, etc. Therefore, since 1972, when the first paper was published on ion-exchanged glass waveguide manufacturing [1], decades of research groups have been dedicating themselves to research on ion-exchanged waveguide technology and development of glass-based PLC devices [2-17]. Up to present days, glass-based PLC technology have been brought out from laboratory into the realm of industrialization, and established itself as a workhorse for fabrication of integrated PLC devices applied in optical communication and optical interconnection networks.

In the process of glass-based PLC device manufacturing, field-assisted ion-migration (FAIM) is a step frequently employed to fabricate buried waveguide from surface waveguide. In this step, driven by direct current (DC) electric field across the glass wafer, doping ions in surface waveguide core layer migrated into underneath the glass wafer surface, surface waveguide being transformed into buried waveguide. Owning to this transformation, glass-based waveguide performance are significantly improved in terms of propagation loss, coupling loss (with single-mode-fiber), and polarization dependence characteristics as well.

In FAIM process for PLC device fabrication, Joule heat generated by electric current through glass wafer influences the process profoundly. One immediate influence is deviation of experimental results from FAIM modeling. For FAIM conducted in constant-voltage (CV) regime, as conventionally adopted for glass-based PLC device fabrication, glass wafer can be heated up to decades of degrees over its nominal temperature; in the mean time, the time span of glass wafer temperature rising accounts a substantial part of waveguide fabrication. FAIM is therefore a non-constant-temperature process. In this context, FAIM models available presently, in which glass wafer temperature is assumed to be constant, will generate results deviated from their corresponding experimental values. The other influence of Joule heat is more disastrous: as has been experimentally shown in [18], with voltage over 300V applied, glass wafer temperature will rise continuously and eventually the glass wafer will be broken, owning to temperature un-uniformity over the wafer.

Therefore, knowledge on glass wafer rising behavior in FAIM is of important significance, it is not only the basis for FAIM model modification, but also a precondition for optimization of FAIM parameters. Experimental method to study glass wafer temperature rising behavior have been reported in [18]. However, to obtain the temperature rising behavior by using solely experimental method is a time-consuming task, and information acquired is limited by the particularity of experimental parameters adopted. In this situation, development of an efficient method to obtain glass wafer rising is of paramount concern. In this paper, a method is presented to simulate glass wafer temperature rising behavior in the process of FAIM. Using this method, information about glass wafer temperature rising can be

comprehensively obtained with high efficiency and reasonable accuracy.

2. Modeling of glass wafer temperature rising

For a glass wafer subjected to FAIM, its temperature rising behavior is determined by competition between two factors: heat generation and heat dissipation. These two factors are therefore two considerations in temperature rise modeling.

One factor is heat generation by Joule heating effect. For a glass wafer subjected to FAIM in CV regime, Joule heat power can be given as:

$$P_{Joule} = \frac{U_0^2}{r(T_{glass})} \qquad (1)$$

where U_0 is assisting voltage applied, $r(T_{glass})$ is electric resistance of the glass wafer, which is expressed as a function of its temperature.

$$r(T_{glass}) = r_0 \exp\left(\frac{Q}{RT_{glass}}\right) \qquad (2)$$

where Q is the activation energy, r_0 is the constant factor, R is the universal gas constant, T_{glass} is the thermodynamic temperature of glass wafer. For a glass wafer made of given material and shaped into given dimensions, Q and r_0 can be determined by linear fitting from a series of experimentally measured glass wafer resistance values at different temperatures [18].

The other factor is heat dissipation. According to heat transfer theory, heat dissipation power from glass wafer to furnace hearth is in direct proportion to temperature difference between the glass wafer and the furnace hearth.

$$P_{dis} = K(T_{glass} - T_{furnace}) \qquad (3)$$

where $T_{furnace}$ is temperature in the furnace hearth, which is conventionally maintained constant during the whole process of FAIM, K is thermal conductance, with its value depends on heat transfer conditions of experimental apparatus. K can be obtained by linear fitting from a series of experimentally measured Joule heating power values at different glass wafer temperatures [18].

With Joule heating power and heat dissipation power given above, thermal balance equation that dictate the glass wafer temperature can be given as follow.

$$P_{Joule} - P_{dis} = \xi_{eff}\frac{dT_{glass}}{dt} \qquad (4)$$

where ξ_{eff} is effective thermal capacity of FAIM apparatus, t is the time of FAIM in second.

Considering (1), (2) and (3), equation (4) can be rewritten as:

$$\frac{U_0^2}{r_0}\exp\left(-\frac{Q}{RT_{glass}}\right) - K(T_{glass} - T_{furnace}) = \xi_{eff}\frac{dT_{glass}}{dt} \qquad (5)$$

Initial condition for equ. (5) can be obtained by finding the glass wafer temperature at the beginning of the FAIM. Obviously, in FAIM process for PLC devices fabrication, glass wafer temperature at the time when voltage is first applied can be deemed as equal to that of the furnace hearth, thus initial condition of the thermal balance equation is:

$$T_{glass}\big|_{t=0} = T_{furnace} \qquad (6)$$

With initial condition equ. (6), glass wafer temperature rising behavior can be obtained by solving equ. (5).

Correspondingly, current flowing through glass wafer can be acquired by

$$I = \frac{U_0}{r_0}\exp\left(-\frac{Q}{RT_{glass}}\right) \qquad (7)$$

Besides the CV regime stated above, constant-current (CC) regime is also frequently adopted in the process of FAIM for glass-based PLC device fabricating. In this regime, current flowing through the glass wafer subjected to FAIM is maintained at a constant value I_0, the Joule heating power generated is thus

$$P'_{Joule} = I_0^2 r_0 \exp\left(\frac{Q}{RT_{glass}}\right) \qquad (8)$$

Correspondingly, the thermal balance equation can be given as:

$$I_0^2 r_0 \exp\left(\frac{Q}{RT_{glass}}\right) - K(T_{glass} - T_{furnace}) = \xi_{eff}\frac{dT_{glass}}{dt}$$

$$(9)$$

Initial condition for equ. (9) can also be determined by finding the glass wafer temperature at the beginning of the FAIM process.

3. Results and discussion

Considering that there does not exists analytical solution for thermal balance equations derived above, numerical method is utilized to find solution to these equations. In this paper, simulations are respectively carried out for FAIM processes conducted in CV and CC regime. Parameters utilized in these simulations are all obtained experimentally. For glass wafers subjected to FAIM experiments, $Q = 130 kJ/mol$, $r_0 = 1.33 \times 10^{-12} k\Omega$; for the FAIM apparatus used, effective thermal capacity ξ_{eff} is estimated to be $264 J/K$, thermal conductance $K = 0.41 W/^{\circ}C$; during the whole FAIM process, furnace hearth temperature is maintained at $237\,^{\circ}C$.

3.1. Temperature rising in CV regime

Fig. 1 shows simulation acquired and experimentally measured temperature rise curves in FAIM process in CV regime, assisting voltage in the range from 50V to 350, at 50V intervals. From this figure, it can be seen that the simulated results are in good accordance with measured values for cases with voltage up to 250V applied; while for cases with higher voltage (300V and 350V) applied, measured temperature rise lags prominently with respect to the corresponding simulated results, due largely to the time consumed for heat transferring from the glass wafer to the thermal couple sensing tip. Nevertheless, the temperature rising trend of simulated curves are in essence similar to the measured curves.

From Fig. 1, it can be seen clearly that with increasing voltage applied across the glass wafer, FAIM in CV regime will become a thermally instable process. The stability mechanism of FAIM in CV regime is illustrated in Fig.2: since glass substrate resistance decreases with its temperature, with constant voltage applied, Joule heat effect becomes stronger as glass wafer temperature rises. In the process of FAIM, if equilibrium cannot be reached between Joule heating and heat dissipation (no crossing between Joule heating curve and heat dissipation curve, as in the cases of 300V and 350V in Fig. 2), in another words, heat generation is always stronger beyond the capability of heat dissipation, glass wafer will rise continuously, and eventually make the process instable.
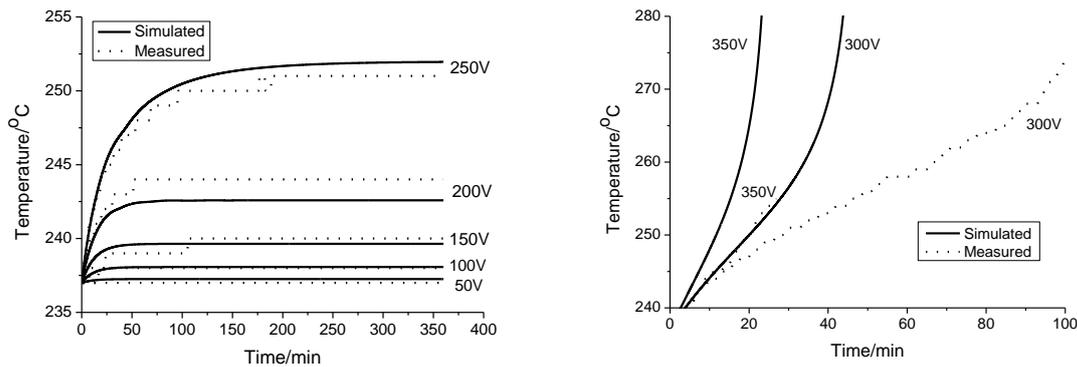

Fig. 1. Simulated and measured value of glass wafer temperature in CV regime. Left: Voltage in the range from 50V to 250V at 50V intervals; right: voltage of 300V and 350V
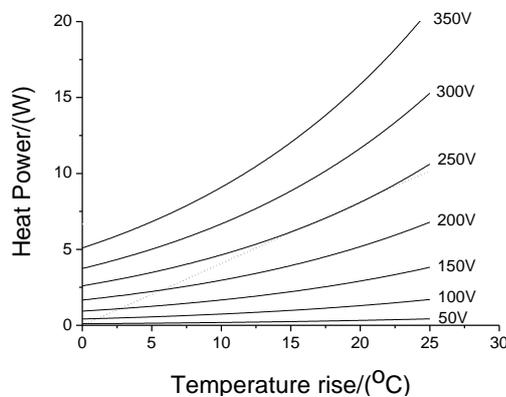

Fig. 2. Dependence of Joule heating power on glass wafer temperature rise (solid lines) in CV regime, and dependence of heat dissipation power on glass wafer temperature rise (dotted line).

Simulated curves of current flowing through the glass wafer, together with measured curves, are shown in Fig. 3, voltage applied in the range from 50V to 350, at 50V intervals. Similar to the case for glass wafer temperature rising, simulated curves of current are also in reasonable agreement with measured results.
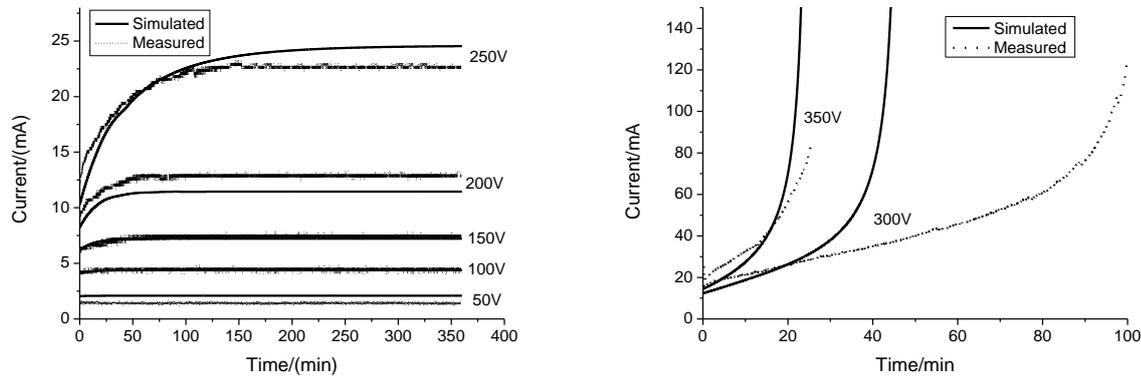
Fig. 3. Simulated and measured curves of current flowing through glass wafer in CV regime. Left: Voltage in the range from 50V to 250V at 50V intervals; right: voltage of 300V and 350V

With this simulation method, other key parameters in FAIM process, glass wafer equilibrium temperature, can be obtained with convenience. Glass wafer equilibrium temperature values at different voltage values, from 0V to 250V, are shown in Fig. 4, in which measured values are also shown.
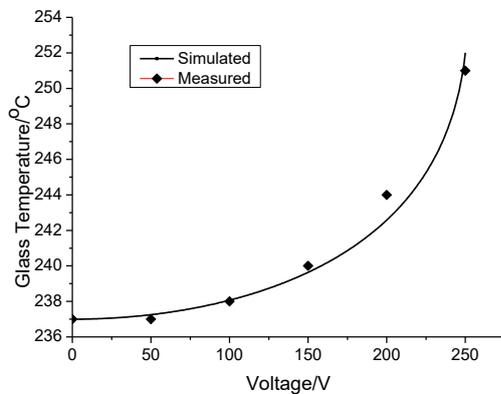

Fig. 4. Dependence of glass wafer temperature at equilibrium state on voltage in CV regime

3.2. Temperature rising inconstant current (CC) regime

Although CV regime is predominate adopted in most of publications on glass-based PLC devices fabrication up to present days, CC regime is very attractive for its inherently thermal stability, as will be demonstrated in the following text.

Glass wafer temperature rising in CC regime is given in Fig.5, current values in the range from 10mA to 100mA, at 10mA intervals. One can see that for each current value, there always exists an equilibrium temperature value. Thermal stability of FAIM in CC regime can be illustrated by using Fig.6: since glass substrate resistance decreases with its temperature, with constant current maintained, Joule heating effect becomes weaker with glass wafer temperature rises. On the other hand, heat dissipation becomes stronger with glass wafer temperature rising. Therefore equilibrium can be reached between Joule heating and heat dissipation, in another word, glass temperature can be stabilized at a certain temperature, irrespective of electric current value. Fig. 7 shows dependence of glass wafer temperature rise amplitude on electric current values.
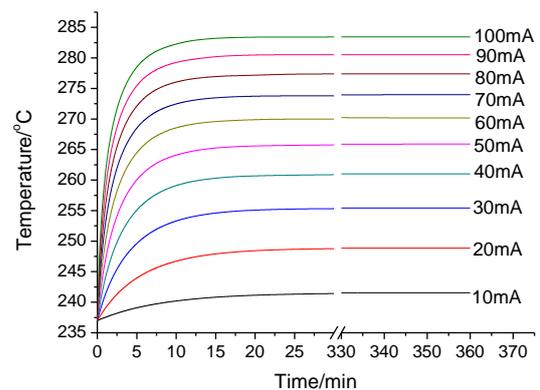

Fig. 5. Simulated glass wafer temperature rising in CC regime, with current value in the range from 10 to 100mA, at 10 mA intervals
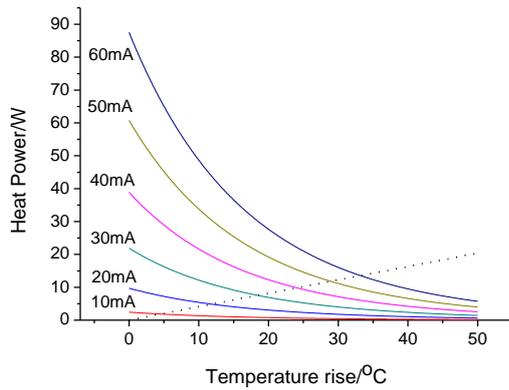
Fig. 6. Dependence of Joule heating power on glass wafer temperature rise (solid lines) in CC regime, with current value in the range from 10 to 60mA, at 10 mA intervals, and dependence of heat dissipation power on glass wafer temperature rise (dotted line)
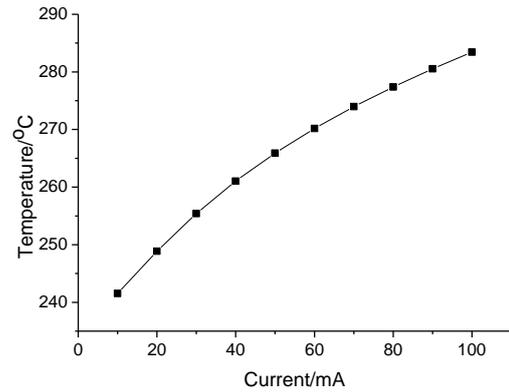

Fig. 7. Dependence of glass wafer temperature at equilibrium state on current in CC regime
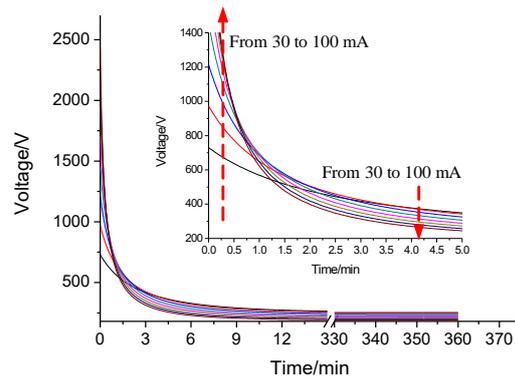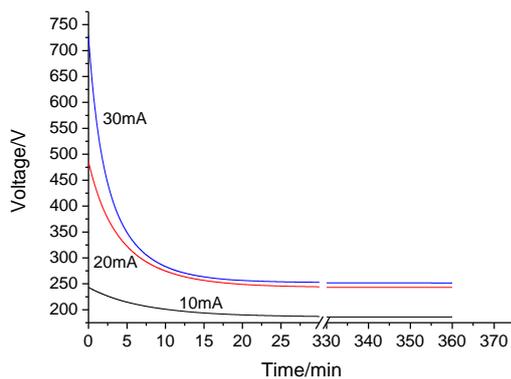

Fig. 8. Simulated value of voltage across glass wafer in CC regime. Left: current of 10mA, 20mA, and 30mA; right: current in the range from 30 to 100 mA, at 10 mA intervals. Insert in right image gives details of curves between in the beginning 5 minutes

For FAIM in CC regime, simulated values of voltage across the glass wafer are given in Fig. 8. One can see that for all cases simulated, stable voltage values can be reached, corresponding to equilibrium between heat generation and heat dissipation. By comparing voltage curves at different current values, one can find an interesting phenomenon: with increasing current, equilibrium voltage does not increase monotonously, but reaches its maximum at 30mA, and then decrease with increasing current.

From Fig. 8, one can see that voltage required at the beginning of FAIM process might be excessively high if high current is applied, e.g. over 2000V for the case of 90mA. Requirement of high-voltage power-supply of such high level is unfavorable for PLC device fabrication, not only for the safety consideration, but also for its low

service efficiency, since the voltage drops rapidly with proceeding of FAIM.

3.3. Temperature rising in CV-CC regime

CV-CC regime, which combine CV and CC regime subsequently have also been utilized in glass-based PLC device fabrication. Fig.9 gives simulation results of voltage and current curve in the process in CV-CC regime. CV regime is first applied before the point that current increasing to 90mA, after which, this current is maintained by using CC regime. From this figure, it can be seen that CV-CC regime can ensure thermal stability of process, but also avoid the application of high-voltage power-supply with high current maintained.
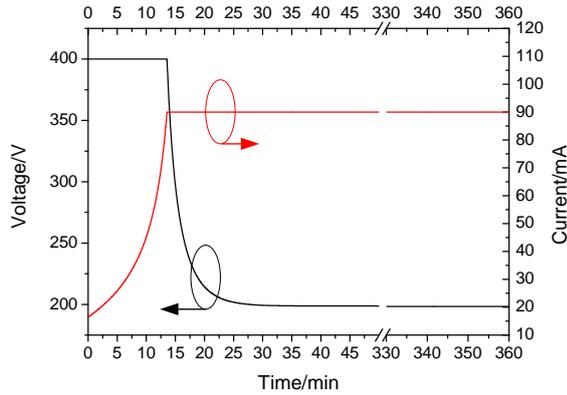
Fig. 9. Simulated voltage and current curves in the FAIM process in CV-CC regime

3.4. Modeling of ion-migration depth

Ion-migration depth a parameter of concern in modeling FAIM process. Conventional models assume that a linear dependence of ion-migration depth on FAIM duration, while considering Joule heating effect, ion-migration depth $d(t)$ can be more precisely expressed as

$$d(t) = M \int_0^t \tilde{i}(\tau) d\tau \qquad (10)$$

where, t is ion-migration time in second, $\tilde{i}$ is current density passing through the glass wafer, τ is variable of integration with dimensionality of time in second, M is a constant, with its value depends on chemical composition of glass wafer material, doping ion specie, etc.

Dependence of ion-migration depth on ion-migration time in CV regime can be conveniently acquired by integrating current density curve, as given in Fig. 10 (left). For convenience of comparison, experimentally measured ion-migration depth values in glass substrate at corresponding voltage are given in Fig. 10 (right). It can be seen that linear dependence of ion-migration depth is deviated with voltage increasing. By comparing simulated and experimentally acquired results, it can be estimated that the proportional constant M is determined approximately to be 0.33 $C \cdot cm^{-2} \cdot \mu m^{-1}$, that is, a charge flux density of 0.33 $C \cdot cm^{-2}$ is passing the glass wafer is corresponding to an increment of 1 μm in ion-migration depth. With M determined, ion-migration depth dependence on FAIM duration can be estimated with higher accuracy.
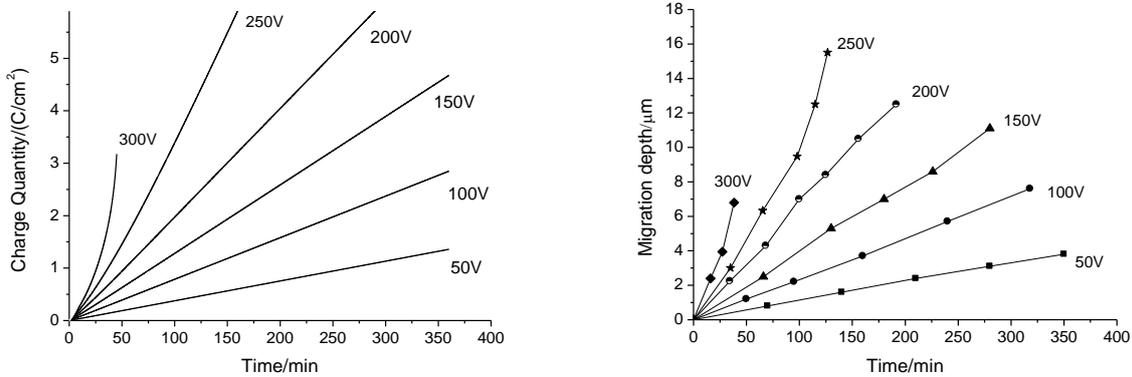

Fig. 10. Simulated charge quantity dependence on FAIM duration in CV regime (left), and measured value of migration depth dependence on FAIM duration in CV regime (right)

4. Conclusions

In conclusion, a method is presented to comprehensively obtain information on glass wafer temperature rise behavior in the process of FAIM. Using this method, glass wafer temperature rise behavior in CV regime can be simulated with high efficiency and reasonable accuracy. This method provides a tool to achieving significant insight into phenomena related with Joule heating effect in the process of FAIM, and besides, it lays a foundation for modifying the existing FAIM model.

References

[1] T. Izawa, H. Nakagome, Appl. Phys. Lett. **21**(12), 584 (1972).

[2] R. V. Ramaswamy, IEEE J. Lightwave Technology **6**(6), 984 (1988).

[3] Seppo Honkanen, Brian R. West, Sanna Yliniemi, et al., Physics and Chemistry of Glasses: European Journal of Glass Science and Technology Part B **47**(2), 110 (2006).

[4] G. Jose, G. Sorbello, S. Taccheo, E. Cianci, V. Foglietti, P. Laporta, Journal of Non-Crystalline Solids **322**, 256 (2003).

[5] F. Gardillou, L. Bastard, J. E. Broquin, Appl. Phys. Lett. **89**, 101123 (2006).

[6] P. Madasamy, S. Honkann, D. F. Geraghty, N. Peyghambarian, Appl. Phys. Lett. **82**(9), 1332 (2003).

[7] Ping Hua, J. Patrick Hole, J. Wilkinson, et al, Opt. Express **13**(4), 1124 (2005).

[8] Yinlei Hao, Hongjian Wang, Bin Zheng, Yubo Li, Jianyi Yang, Xiaoqing Jiang, Qiang Zhou, Minghua Wang, Optical Engineering **51**(4), 044603 (2012).

[9] Tetsuji Yano, Tomonori Nagano, Jaeho Lee, Shuichi Shibata, Masayuki Yamane, Solid State Ionics **150**, 281 (2002).

[10] S. Batchelor, R. Oven, D. G. Ashworth, Electron. Lett. **32**(22), 2082 (1996).

[11] B. R. West, P. Madasamy, N. Peyghambarian, S. Honkanen, J. Non-Cryst. Solids **347**, 18 (2004).

[12] T. Kaneko, J. Phys. D: Appl. Phys. **18**, 2233 (1985).

[13] Ari Tervonen, J. Appl. Phys. **67**(6), 2746 (1990).

[14] Mahmoud Abou-el-Leil, A. R. Cooper, Journal of The American Ceramic Society **62**(7-8), 390 (1979).

[15] G. L. Yip, P. C. Noutsios, K. Kishioka, Optics Letters, **15**(14), 789 (1990).

[16] Peter G. Noutsios, Gar Lam Yip, Applied Optics **31**(25), 5283 (1992).

[17] A. Quaranta, E. Cattaruzza, F. Gonella, Materials Science and Engineering B **149**, 133 (2008).

[18] Yinlei Hao, Bin Zheng, Hongjian Wang, Weiwei Zheng, Jianyi Yang, Xiaoqing Jiang, Qiang Zhou, Minghua Wang, Optical Engineering **51**(1), 014601 (2012).

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